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(71) Applicant (*for all designated States except US*): SCHWARTZ ELECTRO-OPTICS, INC. [US/US]; 3404 North Orange Blossom Trail, Orlando, FL 32804 (US).

(72) Inventors; and

(75) Inventors/Applicants (*for US only*): WANGLER, Richard, J. [US/US]; 2450 Derbyshire Road, Maitland, FL 32751 (US). GUSTAVSON, Robert, L. [US/US]; 730 Sailfish Road, Winter Springs, FL 32708 (US). McCONNELL, Robert, E., II [US/US]; 413 Loblolly Court, Longwood, FL 32750 (US). FOWLER, Keith, L. [US/US]; 55340 Cinderlane Parkway, Orlando, FL 32804 (US). KREEGER, Kevin, A. [US/US]; 115 Randall Avenue, Port Jefferson, NY 11777 (US).

(74) Agent: NAPOLITANO, Carl, M.; Allen, Dyer, Doppelt, Milbrath & Gilchrist, P.A., Suite 1401, 255 South Orange Avenue, P.O. Box 3791, Orlando, FL 32802-3791 (US).

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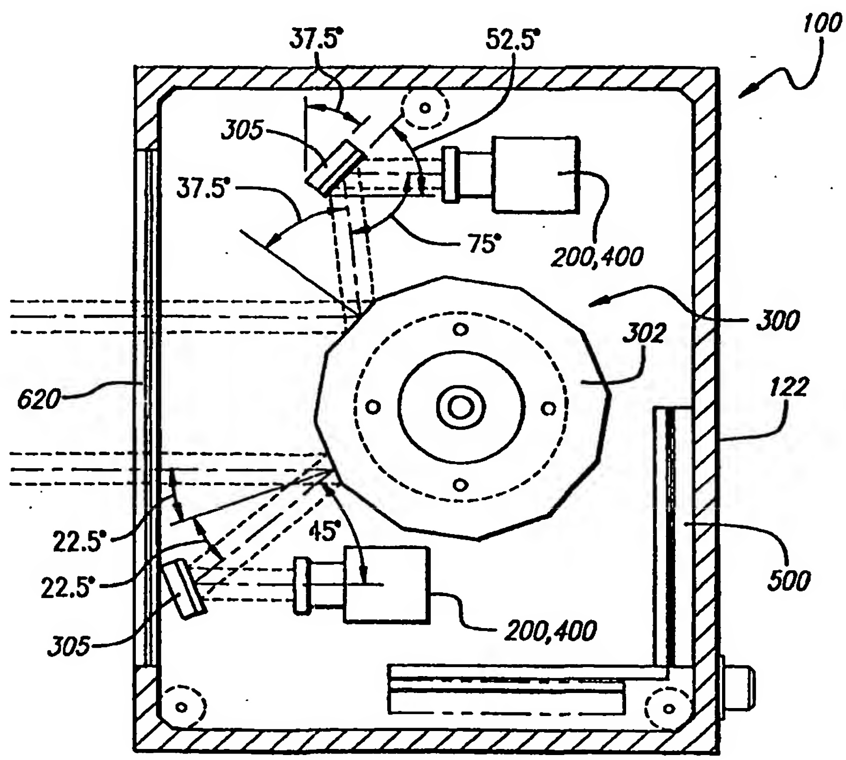
(54) Title: INTELLIGENT VEHICLE HIGHWAY MULTI-LANE SENSOR

(57) Abstract

An Intelligent Vehicle Highway System (IVHS) sensor (100) provides accurate information on real-time traffic conditions that can be used for incident detection, motorist advisories, and traffic management via signals, ramp meters, and the like. The sensor (100), a diode-laser-based Vehicle Detector And Classifier (VDAC) measures the presence, speed, and three-dimensional profiles (128) of vehicles passing beneath it within its multi-lane field-of-view coverage. The sensor (100) uses pulsed laser range imaging technology adapted for determining the three-dimensional profile (128) of the vehicle. A rotating polygon mirror system (300) is used to scan a pulsed laser rangefinder beam across vehicle traffic la nes of a highway (102) in order to measure the presence, speed, and height profiles of vehicules (104) in all lanes simultaneously. A receiver (400) accepts reflections from beams transmitted from the sensor (100) and provides inputs for determining time of flight, and a time interval between interceptions of the two divergent beams, a first beam (106) and a second beam (110) for the vehicle. An encoder tracks the position of a mirror (302) for providing angle data with associated range measurements. High signal-to-noise ratio and good spatial resolution result in highly accurate traffic-parameter measurements.



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INTELLIGENT VEHICLE HIGHWAY MULTI-LANE SENSOR

CROSS REFERENCE TO RELATED APPLICATIONS

This application is related to co-pending U. S. Application Serial No. 08/730,732 filed October 11, 1996 for *Intelligent Vehicle Highway System Multi-Lane Sensor and Method*, and U.S. Provisional Application Serial No. 60/031,383 filed November 20, 1996 for an *IVHS Sensor Beam Scanning Method*, all of which are commonly owned with the present invention.

U. S. GOVERNMENT SUPPORT

This invention was made with United States Government support under Grant No. NAS7-1260 awarded by the National Aeronautics and Space Administration. The U. S. Government has certain rights in the invention.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates generally to object sensors, and in particular to laser rangefinder sensors useful in detecting vehicle speed and shape for classification and input to Intelligent Vehicle Highway Systems (IVHS).

2. Background Art

A vehicle sensor providing the presence of a vehicle in a traffic lane and indicating the vehicle speed as it passes the sensor is disclosed in U.S. Patent No. 5,321,490. A time-of-flight laser range-finder sensor is used to measures a distance to a road surface from a fixed position of the sensor, above the road surface, and measures a distance to a vehicle or vehicles which pass or stop under the sensor.

Two laser beams are pulsed at a high pulse repetition rate and projected across the road surface at a fixed angle between them. Because of the high pulse repetition rate, the system is also able to determine vehicle speed with an accuracy within one mile per hour (mph) and, using a calculated speed, develop a longitudinal profile of the vehicle with consecutive range measurements collected as the vehicle travels under the sensor.

The active near-field object sensor of U.S. Patent No. 5,321,490 provides a sensor which is relatively in low cost, accurate, and useful in a wide variety of applications. The sensor detects the presence of an object within an area located in a close range to the sensor, and includes a range finder having means for emitting a directional output of pulsed energy toward the fixed area. In a preferred arrangement, emitting means comprises a laser diode capable of emitting pulses of coherent infrared radiation, which are used together with collimating optics and a beam splitter to provide two diverging output beams directed toward the near-field area under observation.

The sensor also includes means for receiving a portion of the energy reflected from either the area, or an object located within the area. The returned pulse energy is then provided as an input to a receiver for determining a time of flight change for pulses between the emitting and receiving means, which may be caused by the presence of an object within the area. The sensor is also provided with various features useful in providing outputs which indicate either the speed, census, size or shape of one or more objects in the area. For example, the sensor is provided with means for receiving an input from a time of flight determining means and for providing an output indicating whether the object meets one

of a plurality of classification criteria (e.g., is the object an automobile, truck or motorcycle).

Further, receiving means includes two detectors, with means for alternately selecting between the outputs of the two detectors for providing inputs to the time of flight determining means. Measuring means are also provided for measuring the time interval between interceptions of the two diverging outputs by a given object, so as to calculate the speed of the object passing through the area. Such a sensor is commercially referred to as Autosense I, by manufacturer Schwartz Electro-Optics, Inc. of Orlando, Florida.

As an improvement to the Autosense I sensor of U.S. Patent No. 5,321,490 to Olsen et al., a sensor commercially referred to as Autosense II is provided and described in U.S. Patent No. 5,278,423 to Wangler et al. The sensor of Autosense II incorporates the technology and teachings of Autosense I and provides three dimensional images of objects by rotating or scanning a laser beam range-finder. The scanned laser beam range-finder operates at a high pulse rate, in a plane where there is relative motion between the range-finder and the object to be sensed or imaged in a direction perpendicular to the laser beam plane of rotation. This operation causes the laser range-finder rotating beam, when passing across an object, to cover the object to be sensed with range-finder beam pulses, and thereby, obtain a three dimensional image of the object.

In the Autosense II sensor, Scanning is provided using an optically reflective surface, a mirror, intercepting the beams and reflecting the beams at predetermined angles from a perpendicular to the roadway. Those beams reflected off of the vehicle and directed back toward the mirror are directed into corresponding apertures of the receivers. Means are provided for rotatably moving the reflective surface across

a reflective angle sufficient for reflecting the beams across a transverse portion of the vehicle, and signal means representative of the sensor angle within the beam plane are also provided. The angle signals are delivered to processing means for providing range data at corresponding angles and the range and angle data in combination provide a transverse profile of the vehicle.

There have been suggestions for traffic signal controllers utilizing overhead sensors. Reference is herein made to the following United States Patents: 3,167,739 to Girard et al; 3,436,540 to Lamorlett; 3,516,056 to Matthews; 3,532,886 to Kruger et al; 3,680,047 to Perlman; and 4,317,117 to Chasek. Likewise, near-field sensors have also been utilized as intruder alarms and as automatic door operators. Examples of such arrangements are disclosed in the following United States Patents: 3,605,082 to Matthews; 3,644;917 to Perlman; 3,719,938 to Perlman; 3,852,592 to Scoville et al; 3,972,021 to Leitz et al; and 4,433,328 to Saphir et al. Further, optical dimensioning techniques have been incorporated in industrial uses as disclosed in U.S. Patent No. 4,179,216 and U.S. Patent 4,490,038.

With regard to Intelligent Vehicle Highway Systems (IVHS), a strategic plan for Intelligent Vehicle Highway Systems in the United States was prepared in Report No: IVHS-AMER-92-3 by IVHS America and published on May 20, 1992. The document was produced, in part, under U.S. DOT, Contract Number DTFH 61-91-C-00034. The purpose of the strategic plan is to guide development and deployment of IVHS in the United States. The plan points out that there is no single answer to the set of complex problems confronting our highway systems, but the group of technologies known as IVHS can help tremendously in meeting the goals of the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA). The purpose

of ISTEA is "... to develop a National Intermodal Transportation System that is economically sound, provides the foundation for the Nation to compete in the global economy, and will move people and goods in an energy efficient manner." It is a worthy goal to satisfy the needs identified within the ISTEA. The IVHS America plan describes these needs, one of which is Automated Vehicle Classification (AVC).

SUMMARY OF INVENTION

In view of the foregoing background, it is therefore an object of the present invention to further expand on the capabilities and use of the Autosense II sensor and provide a sensor capable of detecting multiple vehicles traveling within multiple parallel lanes of traffic with sufficient accuracy for classifying the vehicles. Because the sensor of the present invention accurately (± 1 mi/h, 1σ) measures vehicle speed as well as vehicle count, it provides the basic data from which other traffic parameters, such as flow rate and mean speed, can be derived. A distinguishing feature of the Autosense sensors which sets the sensor apart from other vehicle detectors, is the ability to accurately measure vehicle height profiles. This unique capability is utilized to classify vehicles and to identify specific vehicles when matched with downstream sensors for the determination of travel time. It is yet another object of the invention to improve upon the vehicle sensors earlier described by providing improved scanning across multiple lanes of traffic. It is thus a further object of the present invention to provide improvements to the IVHS sensors and methods by providing a beam scan measurement adjustment to compensate for non-parallel roadway surface scan lines resulting from a beam reflected from multiple facets of a rotating polygon.

As with earlier Autosense versions, it is further an object of the invention to provide information useful to other Intelligent Vehicle Highway Systems and the Electronic Toll and Traffic Management (ETTM) area, in particular to Automatic Toll Collection. The present invention is directed toward uses of the Autosense series of sensors and in particular to improvements packaged in what is commercially referred to as Autosense III, as described in the above referenced co-pending U.S. utility and provisional applications.

These and other objects, advantages, and features of the present invention are provided by a sensor comprising laser rangefinder means for determining a range from the sensor to points on a vehicle when the vehicle travels within a sensing zone and for providing range data outputs corresponding to sensor angles for ranges from the sensor to the points on the vehicle, means for scanning the laser means within a plane generally orthogonal to a direction of travel for the vehicle, the scanning means communicating with the laser rangefinder means for determining a range for a corresponding point on the vehicle within the transverse plane, the scanning means providing means for determining the range and a corresponding sensor angle for each point within the scanning plane, deflecting means cooperating with the scanning means for deflecting the scanned beam from a first longitudinal position to a second longitudinal position, the first and second positions defining a forward and backward beam for receiving the vehicle traveling in a directing between the beams, and means for processing the ranges, corresponding angles, and interception times for the vehicle receiving the first and second beams, the processing means providing a vehicle image profile representative of the vehicle.

The sensor in a preferred embodiment comprises a forward and a backward beam emitted by the laser means. The forward and backward beams are separated by a predetermined angle and are emitted toward a fixed area through which the vehicle travels. A time signal representative of a travel time for a point on the vehicle to travel between the beams is determined from time-of-flight data provided by the range data processing means. A transmitter and receiver, along with a rotating polygon mirror are used for emitting a pair of laser beams, for directing the beams toward zones on a roadway traveled on by the vehicle, and for converting reflected laser beams from the vehicle to signal voltages representative of ranges between the receivers and defined points on the vehicle.

Scanning is provided using an optically reflective surface intercepting the beams and reflecting the beams at predetermined angles from a perpendicular to the roadway. The beams reflected off of the vehicle are directed back toward the mirror into corresponding apertures of the receivers. Means are provided for rotatably moving the reflective surface across a reflective angle sufficient for reflecting the beams across a transverse portion of the vehicle, and signal means representative of the sensor angle within the beam plane are also provided. The angle signals are delivered to the processing means for providing range data at corresponding angles and the range and angle data in combination provide a transverse profile of the vehicle.

In one embodiment, the scanning is provide using a mirror intercepting the beams emitted from the transmitter and reflecting the beams onto scanning planes. The planes are set at opposing angles from a perpendicular to the roadway. The reflected beams directed back toward the mirror are directed into corresponding apertures of the receiver. A motor having

a rotatable shaft is affixed to the mirror for continuously rotating the mirror about the axis, and an encoder is affixed to the motor shaft for identifying an angular position of the mirror relative to a reference angle.

Processing means comprises a microprocessor programmed to receive respective range and sensor angle data for storing and processing the data for a scanned cycle associated with a timing signal. The processed data results in a three dimensional shape profile for the vehicle. Further, the invention comprises an algorithm for comparing the vehicle shape profile with a multiplicity of predetermined vehicle shapes for classifying the vehicle.

Related applications referenced above describe an evolution of laser range finder sensors beginning with the sensor disclosed in U.S. Patent No. 5,321,490 using a fixed bifurcated infrared laser beam to measure vehicle speed, presence, count, and its two dimensional profile. Improvements disclosed in U.S. Patent No. 5,546,188 included a sensor having a scanning infrared laser beam for measuring vehicle speed, presence, count, a three dimensional profile, and vehicle classification based on the profile as the vehicle crossed a sensing area within a traffic lane. The improved sensor, herein described, optimizes the use of the three dimensional sensing capability and combines elements of the sensor for monitoring multiple traffic lanes for developing vehicle profiles for as vehicles pass through the sensing area comprising the multiple lanes. The disclosure of the above related applications is relied upon and incorporated herein by reference for supporting disclosure. However, the present specification includes disclosure from these related applications for convenience and completeness, as well as new disclosure which together will enable any person skilled in the art to make and use the sensor of the present invention.

While particular exemplary embodiments are disclosed in both methods and apparatus for this invention, those of ordinary skill in the art will recognize numerous possible variations and modifications. All such variations are expected to come within the scope of the present invention.

BRIEF DESCRIPTION OF DRAWINGS

A complete and enabling disclosure of the present invention, including the best mode thereof, is directed to one of ordinary skill in the art in the present specification, including reference to the accompanying figures, in which:

FIG. 1 is a partial perspective view illustrating an IVHS sensor of the present invention in one sensing configuration;

FIG. 2 is a partial elevation view of the sensor of the present invention operating with multiple traffic lanes;

FIG. 2A is a partial perspective view of sensor geometry illustrating an alternate configuration of forward and backward scanning laser beams used in one preferred embodiment of the present invention;

FIG. 3 is a schematic diagram of a preferred embodiment of the sensor of the present invention;

FIG. 4 is a partial top plan view of a sensor packaging of FIG. 3;

FIG. 5 is a perspective view of the multi faceted mirror of FIG. 4;

FIGS. 6 and 7 are diagrammatic functional representations of a multi faceted mirror used in one preferred embodiment of the present invention;

FIG. 8 is a block diagram illustrating electronics and optics of one embodiment of the present invention;

FIG. 9 a schematic diagram of the time to amplitude (TAC) and logic circuitry useful in the sensor of the present invention;

FIG. 10 is a perspective view illustrating a three dimensional vehicle profile provided by the present invention;

FIG. 11 is a pen and ink reproduction of a false color range image illustrating vehicle profiles for detected vehicles;

FIGS. 12A and 12B are block diagrams illustrating a functional flow of a processor used for the present invention;

FIGS. 13A through 13J illustrate "American Truck Association Truck Types" by way of example, for use in toll road vehicle data collection and classification;

FIG. 13K is a perspective view illustrating a three dimensional truck profile provided by the present invention illustrated with a black and white ink tracing of a monitor screen;

FIG. 14 and 15 are perspective views illustrating operation of the active near-field object sensor;

FIG. 16 is a block diagram illustrating electronics and optics of an alternate embodiment of sensor illustrated in FIGS. 14 and 15;

FIG. 17 illustrates a scan geometry for providing high accuracy laser radar with a three inch range resolution for a sensor of the present invention;

FIG. 18 diagrammatically illustrates use of a rotating twelve sided polygon mirror to scan a beam with a dual-position nodding mirror deflecting the beam onto alternate rotating mirror facets for reflecting a beam into forward and backward scanned beams;

FIG. 19 is a schematic diagram of an embodiment of the present invention illustrating use of two transmitters and two receivers for forming the forward and backward scanned beams;

FIG. 20 is a functional block diagram illustrating direct and indirect sensor functions;

FIGS. 21 through 27 are interrelated flow charts illustrating a preferred embodiment of software useful with the present invention;

FIG. 28 is a top plan view diagrammatically illustrating a test lab layout used for beam separation measurements;

FIG. 29 is a side elevational view of the test lab layout of FIG. 28;

FIG. 30 illustrates beam scan traces on a test surface;

FIG. 31 illustrates a coordinate system used for angular separation analysis in one preferred embodiment of the present invention;

FIG. 32 illustrates a laser beam reflectance from a tilted polygon facet; and

FIG. 33 is a plot of a predicted and measured reflected beam tilt angle as a function of sensor scan angle.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENT

The present invention will now be described more fully hereinafter with reference to the accompanying drawings, in which preferred embodiments of the invention are shown. This invention may, however, be embodied in many different forms and should not be construed as limited to the embodiments set forth herein. Rather, these embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the invention to those skilled in the art. Like numbers refer to like elements throughout.

As illustrated with reference to FIG. 1, in preferred embodiments of the present invention, a sensor **100** is affixed above a highway **102** for sensing a vehicle **104** passing below the sensor **100**. A first or forward scanned beam **106** intercepts the vehicle **104** as the vehicle **104** crosses the forward beam **106** and enters a sensing area **108** below the sensor **100** configured and described herein by way of example. A second or backward directed and scanned beam **110** intercepts the vehicle, designated as numeral **104a**, as the vehicle **104a** leaves the sensing area **108**. By way of example, and illustrated herein with reference again to FIG. 1 and to FIG. 2, for traffic surveillance applications, the sensor **100** is mounted on cables or a mast arm **112** over the highway **102**. The improved sensor **100** herein described is mounted overhead and centered over multiple lanes, between three lanes **114** of traffic as herein described by way of example. In one preferred configuration of the present embodiment, and as illustrated with reference again to FIG. 2 and to FIG. 2A, the sensor **100** is mounted over the center lane **115** of traffic with look-down angles of 10 degrees for the forward beam **106** and 0 degrees for the backward beam **110**. Although it is anticipated that various angles will be used, this mounting

configuration provides for good spatial resolution and reduces shadowing caused by larger vehicles. A total beam scan coverage **116** is 60 degrees, and when the sensor **100** is mounted at 30 feet above the highway **102**, complete lane coverage for three 12 ft. lanes **114** typically found for the highways **102** relying on IVHS sensors.

As illustrated with reference to FIGS. 3 and 4, two beams **105**, **109** comprise 904 nm radiation which are emitted by two similar transmitters **200**. Each of the beams **105**, **109** are directed for scanning across 30 degree scan angles with the transmitters **200** positioned for scanning the total 60 degree coverage **116**. In addition, each beam **105**, **109** is again split for having an angular forward and backward separation of 10 degrees, which beams **106**, **110** are directed toward the highway **102** as earlier described with reference to FIGS. 1 and 2. Although most of the emitted radiation, illustrated by numerals **106a**, **110a**, is specularly reflected away using a mirror system **300**, a small amount is diffusely reflected back to the sensor **100**, as illustrated by numerals **106b**, **110b**, where it is detected by a pair of receivers **400**. The round-trip propagation time of a laser pulse making up the beams **106**, **110** is proportional to a range **118** to the vehicle **104** or the highway **102** from which the radiation is reflected. The presence of the vehicle **104** is indicated by a reduction in the range reading from the vehicle range **118** to a highway range **120**. Vehicle speed is computed from the measured time interval between the interceptions of the forward and backward beams **106**, **110**. On-board microprocessors **500**, within the sensor housing **122**, are used for the determination of vehicle presence, speed, count, and classification, as will be described in further detail later in this section. A real-

time clock is used to time-tag the data collected to provide, by way of example, vehicle count and average speed for each hour of the day.

As illustrated again with reference to FIGS. 3 and 4, the sensor **100**, a laser rangefinder apparatus, employs a pair of InGaAs diode-laser transmitters **200** and silicon avalanche photodiode (APD) receivers **400** in a generally side-by-side configuration. Each transmitter **200** consists of a laser diode **202**, its laser driver **204**, and a collimating lens **206**. Each optical receiver **400** is comprised of an objective lens **402**, a narrow-band optical filter **404**, detector/ amplifier **406**, and a threshold detector, described in above referenced applications and herein later described in further detail.

The laser diode **202** used in a preferred embodiment of the present invention includes an InGaAs injection laser diode having 12 W output at 10 Amps pulsed current drive. The laser driver **204** produces a 10 Amp peak current pulse with a 3 ns rise time and an 8 ns pulse width. A trigger pulse from a scanner controller, as will be further described later in this section with discussions of the mirror system **300**, triggers the laser transmitter **200** at preselected scan angles produced by the mirror system **300**. The 904 nm laser beam emission is at an ideal wavelength for the silicon APD receivers **400** used.

The sensor **100** of a preferred embodiment of the present invention includes a rotating polygon scanner **302** to line scan the laser beams **106**, **110** across the three 12-foot-wide lanes **114** of a highway **102**, as earlier described, by way of example, with reference to FIGS. 1 and 2. In a preferred embodiment, the polygon scanner **302** rotates continuously in one direction **304** at a constant speed. As herein described,

for coverage of the lanes **114**, and as illustrated with reference to FIGS. 5 through 7, as the polygon scanner **302** rotates, the transmitted beams **105**, **109**, earlier described with reference to FIG. 3, are scanned across a polygon scanner reflective flat facet **308**, changing an angle of incidence as the facet **308** is rotated about the scanner axis or rotation **310** for providing the beam scan coverage **116**. Thus, each transmitter **200** and receiver **400** pair is scanned by the rotating polygon **300** to provide the 30 degree coverage for each, and when sequentially processed, the full 60 degree coverage **116** is achieved.

As illustrated with reference again to FIG. 5, there is an angular separation **306** between facets **308**. By way of example, each adjacent facet **308a**, **308b** is set at ten degrees. In the embodiment illustrated again with reference to FIGS. 5 through 7, alternating adjacent facets **308a**, **308b** have angles **309a**, **309b** to a polygon base **310** which angles alternate between 87.5° and 92.5° for the adjacent facets **308a**, **308b**. As a result, successive scans are made with the angular separation **306** of 10 degrees, for providing the separated forward beam **106** and backward beam **110** used in vehicle speed measurements. It should be understood that when laser beam scanning is discussed, the laser beam receiver **400** has a field-of-view also scanning since the laser beam axis and receiver field-of-view are aligned and therefore the returned reflected beam herein illustrated is collinear.

With one preferred embodiment of the sensor **100** comprising the mirror system **300** having the rotating polygon scanner **302** described with reference to FIG. 5, the range processor **502** described with reference to FIGS. 3 and 8, keeps track of the scanner **302** position using incremental readings

from the shaft encoder **312** within mirror electronics **315** of the sensor **100**. Therefore, the facets **308** and beam angle **138**, as illustrated again with reference to FIG. 1, at which a range measurement is being taken, is known. A representative signal **317** is provided to the range processor **502**, as illustrated again with reference to FIG. 8. The shaft encoder **312** triggers the laser driver **208** with a first set of consecutive pulses which provide the scanned beam **106** at a predefined angle and will be offset by another set of consecutive pulses resulting from the rotating scanner **302** and reflections from its facets **308** and the discontinuities between facets **308**. Again with reference to FIG. 8, the sensor **100** as herein described, comprises dual transmitters **200** and receivers **400**, as illustrated and described with reference to FIGS. 3 and 4. As will be later described, alternate embodiments of the mirror system **300** include the use of nodding mirrors **318** and positioner **320** described with reference to FIG. 8 herein and in above referenced application.

In addition, to optimize the size of the sensor housing **122**, as illustrated again with reference to FIGS. 3 and 4, folding mirrors **305** are used to redirect beams from each transmitter **200** and receiver **400** pair to the polygon scanner **302**. In an alternate embodiment, the nodding mirror **318** may serve a similar function for directing the beam through the housing window **620**, described later with reference to FIG. 16.

As is described in U.S. Patent No. 5,546,188, and herein again described with reference to FIG. 8 and again with reference to FIG. 3, the optical detection of the reflected beams **106b**, **110b** includes circuitry which converts optical radiation reflected from the vehicle **104** and highway **102**, as

earlier described with reference to FIG. 1, to first, an equivalent electrical analog of the input radiation and finally, a logic-level signal. With reference again to FIGS. 3 and 8, the output **410** of each receiver **400** is multiplexed by the microprocessor **500** and is connected to a peak detector **412** that measures the intensity of the reflected pulse. Each receiver **400** also contains a threshold detector **414** which converts the analog return pulse signals to logic-level pulses. The logic-level signals are processed within the range counter logic circuitry **416** to yield analog range data, which is read by the microprocessor **500**.

While it is appreciated by those skilled in the art that both digital and analog techniques may be used for making the time interval measurement in order to accurately measure the propagation time of the laser pulse to the target and back to the receiver, the analog technique was chosen in earlier embodiments as well as a preferred embodiment of the present invention because of its better resolution, smaller size, simpler circuitry, lower power consumption and lower costs when compared with the digital technique. The analog range measurement technique specifically used in the present invention is known as a "time-of-flight converter" and has an accuracy of about one percent of measured range and a resolution of about plus or minus five centimeters. As illustrated with reference to FIG. 9, the logic circuit **416** comprises range gate **418** and time-to-amplitude converter (TAC) circuit **420** which uses a constant current source **421** including transistor Q1 to charge a ramp capacitor C38, identified with numeral **422**, to obtain a linear voltage ramp whose instantaneous value is a measure of elapsed time. The TAC circuit **420** is designed so that the voltage across the capacitor C38 **422** begins ramping down from the positive power

supply when the transmitter **200** fires to provide a start signal **422**, illustrated again with reference to FIG. 8. The ramp is stopped when either a reflected pulse is received by the receiver **400** to provide a stop signal **423** or at the end of a measured period of time. A maximum range and thus a maximum measured time period is preselected as an initial value. The output of the TAC circuit output **424** is then converted to a digital format by a ten bit analog-to-digital converter within the microprocessor **500**.

The timing pulse start signal **422** for the TAC circuit **420** is generated by a shaft encoder **312** with a simultaneous pulse causing the laser transmitter **200** to fire.

Such pulsed time-of-flight range measurements using the TAC circuit **420** provide accurate (typically within 3 in.) transverse height profiles of the vehicle **104** on each scan. The vehicle speed, determined from the time interval between the interceptions of the two laser beams **106**, **110**, as earlier described with reference to FIGS. 1, 6 and 7, by the vehicle **104**, is used to space, with a scan separation distance **124**, transverse profiles **126** appropriately to obtain a full three-dimensional vehicle profile **128**, as illustrated with reference to FIG. 10. An algorithm, as will be described in further detail later in this section, is applied to the three-dimensional profile **128** for vehicle-classification purposes.

One preferred embodiment of the present invention includes two microprocessors **500**, a range processor **502** and a data processor **504**, as illustrated again with reference to FIG. 3. The range processor **502** triggers the transmitter **200** as earlier described, reads the real-time range and intensity data, provided by the peak detector **412** and TAC circuit **420**, as earlier described, and runs continuous self test and

calibration functions. The data processor **504** runs all the algorithms for vehicle classification, calculates certain traffic parameters, and controls all communications ports, for example an RS232 output.

An example of three-dimensional profiling capability for multiple vehicles within multiple lanes is provided by the range images shown in FIG. 11. This range image of a van **130** traveling next to a small truck **132** traveling at a speed of about 45 mph demonstrates the ability of the sensor **100** to distinguish between vehicles **104**. The pixel spacing resulting from a 0.67 degree scan resolution is more than adequate for vehicle separation.

When the vehicles **104** are present beneath the sensor **100**, as illustrated again with reference to FIGS. 1 and 2, the distance to a top surface of the vehicle **104** will be measured. As illustrated again with reference to FIG 10, these measured distances at various scan angles, earlier described with reference to FIG. 1, are used to generate the vehicle profile **128** (height above the highway **102**) by straightforward geometric transformation. If the vehicle **104** is stationary, the laser beam **106**, by way of example, will continuously scan across it along the same line. If the vehicle **104** is moving, the scans will be separated by the scan separation distance **124** determined by the vehicle speed and the scan repetition rate. The scan separation distance **124** scan separation distance is

$$ds=V/SR$$

where V is the speed of the vehicle and SR is the scan rate (beam scan per second). The 12-sided polygonal mirror **302**, illustrated again with reference to FIGS. 3 and 5, rotates at 3600 rpm and as earlier described, has every other facet **308** tilted, which results in a scan rate of:

SR=(3600/60) X 6 = 360 scans/sec/scan line

By way of example, for a vehicle speed of 100 mph, the separation distances **124** for consecutive profiles are less that 5.0 inches, and for 50 mph the separation distance **124** is less than 2.5 inches. Using the consecutive cross-lane profiles, the three-dimensional images **128**, **130**, **132**, with reference again to FIGS. 10 and 11 are constructed. At 100 mph, the scanner produces 72 scans across a 15-foot-long vehicle. With each scan containing 30 range measurements, there are at least one thousand to two thousand range measurements (depending on vehicle width) at 100 mph, by way of example. This high scan rate combined with full lane coverage, narrow laser beam width and 3″ range accuracy makes it difficult for a vehicle to pass through the sensing area **108** undetected. Even closely-spaced vehicles (by way of example within 1-2 ft) traveling at 100 mph are easily separated.

As illustrated again with reference to FIGS. 1 and 10, a vehicle length (l) **135** is calculated by measuring the vehicle speed (v) and multiplying it by the total number of scan lines (sl) or transverse profiles **126** detected on the vehicle **104** and the scan-to-scan time (st) using

l = v X sl X st

Since the scan-to-scan time of the scanner is measured with ±1 μs accuracy by a controller **314** for the rotating polygon scanner **302**, the length accuracy will have the same speed-dependent accuracy as the speed.

The sensor **100** is capable of classifying vehicles such as a motorcycle, automobile, pickup truck, bus, and commercial trucks. This list can also be expanded by breaking a vehicle class into subcategories. For instance, the sub-

classification categories can be generated to separate pickup trucks from vans or sport utility vehicles.

Each sensor **100** provides both an RS-232 and an RS-422 serial interface **506** for connection to other equipment. The RS-232 interface operates at data rates up to 19.2 kilobits per second and is primarily used to connect the sensor to spread-spectrum radio links or other types of data modems. Hard-wired installation of the sensors **100** is better served by the RS-422 interface. With this port, data rates of up to 1.0 megabits per second (during test mode) can be supported.

Features of the sensor **100** include, automatically initializes the vehicle detection process upon power up, automatically adjusting for varying conditions at the installation sites, including adjustments for slope, grade, road reflectivity variations, and the presence of barriers and guard rails. Such features and sensor performance are not compromised by vehicles passing through the sensing area **108** or field-of-view.

The continuous self-test capability of the sensor **100** provides instant fault isolation. Every major circuit in the sensor is continuously tested for proper operation. The moment any self-test fails, a Self-Test Message will be transmitted from the unit so that immediate action can be taken if necessary.

Testing of the sensor **100** has determined a detection accuracy of 99.9%, speed accuracy of +/- 3.5 mph @ 60 mph, and a classification accuracy of 98% for 5 classes. The increased lane coverage of the sensor **100** herein described with reference to FIG. 3, results in a reduction in the number of sensors needed for larger roadway configurations. Mounting variations could utilize the sensor **100** for coverage of additional lanes other than the three herein described, by way

of example with reference to FIG. 2. To provide a thorough and complete disclosure and fully convey the scope of the present invention, its improvements with regard to earlier disclose embodiments, consider the following, again with reference to FIG. 3 and with reference to FIGS. 12A and 12B, the microprocessor **500** receives range information through the TAC output signal **424** and return pulse intensity signal **426**, as described earlier. In addition, time walk corrections are performed for accounting for range measurement error and for providing a corrected range signal **508** used with a respective angle signal **428** provided by the shaft encoder **312**, earlier described with reference to FIG. 8, for providing a cosine correction **510** in the scanning plane and results in a range data set **512** representative of a sensed surface such as the detection points **136** on the vehicle **104**, as described earlier with reference to FIG. 1. This range data set **512** is then processed in the data processor **504** for classification with known vehicles. As earlier described, the forward and backward beams **106**, **110** are distinguished and corresponding forward scan **430** and backward scan **432** signals are input to the microprocessor **500** for use in time calculations to determine the vehicle speed. In this way, the three dimensional vehicle profile illustrated in FIG. 10 is constructed with reference to the highway **102**. Profiles **128** are matched against database profiles in the data processor **504**. Predetermined rules for comparison are used that will include, by way of example, total vehicle surface area, vehicle height above the roadway, and other distinguishing database vehicle characteristics effective in classifying the vehicles. Once the rules are established, general rule base algorithms are used in completing the classification. By way of example, and with reference to

FIGS. 13A through 13J, the complexity of the classification can be appreciated by examining the truck types established by the American Trucking Association as one example. It is anticipated that multiple sensors **100** will be used to provide classification in certain situations where additional detail for a vehicle or multiple vehicles in multiple lanes is required. By way of example, a reconstructed three dimensional profile of a truck is illustrated with reference to FIG. 13K, for a typical image as viewed on a video monitor screen.

As earlier discussed, disclosure of a sensor **600**, as illustrated with reference to FIGS. 14-16, will further support disclosure of the improved sensor **100** and provide an appreciation of sensor history, the sensor **600** being earlier referred to as Autosense I. In addition, features found to support improved sensors, Autosense I and II, operation are included for the sensor **100**. The sensor **600**, comprises a compact enclosure **612** of light-weight material, such as aluminum. Across one side of the enclosure **612** is a transmissive window **620**, which is shielded from ambient weather by a hood **618**.

An electro-optical assembly fitted within the enclosure **612** is depicted in a block diagram format with reference to FIG. 16 and referred to there generally by the reference numeral **628**. The electrical-optical assembly **628** includes a transmitter section **630**, a receiver section **632**, a range/processor section **634**, and a power supply **636**, each of which is discussed in detail in U.S. Patent No. 5,321,490 and as highlighted below.

As illustrated with reference again to FIG. 16, the transmitter section **630** includes an astable multivibrator **602** generating a laser trigger pulse at a nominal repetition

frequency of 3 kilohertz to a laser driver **604** which, by way of example, produces a 20 ampere peak current pulse with a 4 nanosecond rise time, and a ten nanosecond pulse width. The output of the laser driver controls a laser diode **606**, which preferably comprises an indium gallium arsenide injection laser diode array having an output on the order of 180 watts, at the 20 ampere pulse current defined by the driver **604**. This diode emits an output at 904 nanometers, which has been found to be an ideal wavelength for the silicon photodiode receiver, discussed below. It is also preferred that the array of the laser diode **606** have a junction characterized by dimensions of about 3.96 millimeters by 0.002 millimeters, in order to emit radiation in a 10 degree by 40 degree solid angle.

The output of the laser diode array **606** is collected by a fast (F/1.6) multi-element optical lens **608** which has an effective focal length of 24 millimeters and which is used to collimate the diode laser emission, the resulting collimated beam passes through a dual-wedge prism **610**. By way of example, the resulting beam has a divergence of 3.96/24 = 165 mrad parallel to the diode junction and 0.002/24 = 0.083 mrad perpendicular to the diode junction. The two outputs of the dual-wedge prism **610** are referred to by reference numerals **609** and **611**. Both outputs are passed through the heated transmissive window **620**.

In order to generate the high voltage necessary to pulse the laser diode **606**, a 200 volt DC-DC converter **612** is provided in the transmitter section **630** and preferably is contained within the aluminum enclosure **612**, earlier described with reference to FIGS. 14 and 15, for reducing electrical interference.

The transmitter section **630** further includes an optical fiber **614** coupled to receive a simultaneous output from the laser diode **606** with the emission into the lens **608**.The output passing through the optical fiber **614** provides a significant aspect of the sensor **600**, as is discussed in greater detail with reference to the range/processor section **634**.

The receiver section **632** includes lens **622** for receiving reflected returning energy from the two pulsed output beams **609**, **611** emitted by the transmitter section **630**. The energy passing through the lens **622** is passed through an optical filter **624**, and the single input from the lens **622**-filter **624** is fed into two photodetectors **626**, **628** each of which provides an input to a respective amplifier **627**, **629** both of which provide an input to an analog multiplexer **632**. The sensor **600** performs an optical multiplexing. The optical energy received in the lens **622** is first converted into an equivalent electronic analog of the input radiation and second into a logic-level signal. The outputs of the two photodetectors **626**, **628** are time-multiplexed by the high-speed analog multiplexer **632**, which is controlled by a logic-level control line **633** from the microprocessor **652** contained within the range/processor section **334**. The output of the multiplexer **632** is connected to a threshold detector **636** and an amplifier **634**, both of which provide inputs to the range/processor section, as described below.

In one preferred configuration, the two photodetectors **626**, **628** are silicon photodiodes which operate as current sources, with the associated amplifiers **627**, **629** converting the current pulses of the photo detectors **626**, **628** into voltage pulses. Each amplifier **627**, **629** offers a

transimpedance of 28 kilohms when operated in a differential mode.

The optical filter **624** preferably has a narrow-band (on the order of 40 nanometers) width, which limits the solar radiance and permits only the 904 nanometer radiation to reach the photodetectors **626**, **628**. Typically, the transmission of the narrow-band filter **624** is on the order of about 75 percent at 904 nanometers.

It is preferred that the analog portion of the receiver section **632** be contained within a Faraday shield (not shown) which permits the circuit to operate in a "field-free" region where the gain is achieved without additional noise reduction.

Again with reference to FIG. 16, the range/processor section **634** includes a detector **642** optically coupled with the fiber **614**, an amplifier **643** and a threshold detector **644**, the output of which represents a "start" input to a range gate **646**. The "stop" input for the range gate **646** is provided as the output from the threshold detector **636** contained within the receiver section **632**.

The specific forms of the range gate **646** and the time-to-amplitude (TAC) converter circuit **420** are shown described in the co-pending applications and described earlier in with reference to FIG. 9. A constant-current source including transistor Q1 is used to charge a ramp capacitor C38 to obtain a linear voltage ramp whose instantaneous value is a measure of elapsed time. The TAC circuit **420** is designed so that the voltage across the capacitor C38 begins ramping down from the positive power supply when the laser diode **606** fires. The ramp is stopped when either a reflected pulse is received at the detectors **626** or **628**, or at the end of a measured period of time. The output **649** of the TAC circuit **420** is then converted to a digital format by an 8 bit analog-to-digital

converter inside the microprocessor **652**. The start timing pulse for the TAC circuit **420** is produced utilizing the optical detection of the transmitted laser pulse through the fiber **614**, which provides an input to the detector **642** and thence to the amplifier **643**.

Further referring to FIG. 16, the output of the amplifier **634** from the receiver section **632** is provided as an input to a peak detector **650** which in turn provides an input to the microprocessor **652**. This feature is directed to a problem encountered when measuring range-to-vehicles in the low level of return signals from windshield and poorly reflecting black metal or plastic vehicle parts. This low level of return signals frequently results in range readings which are close to those from the street level, and would therefore erroneously indicate that a vehicle was not present. This range measurement error, which is proportional to the magnitude of the variation in return-signal level, is known as "timing walk". This problem is solved by the accurate measurement of the peak of the return signal with the high-speed peak detector circuit **650**, and the use of the microprocessor **652** to apply a correction factor to the range measurement based on the return signal level. Thus, a very low level of the signal is in itself an indication of the presence of an object (such as a vehicle) being detected. The sensor will then indicate the presence of the object when either the range reading is shorter than that to the street, or alternatively when the return-signal level is much less than that from the street.

The microprocessor **652**, by way of example, comprises an Intel 87C196KC into which the software described below is loaded. As noted in range/processor section **634**, the microprocessor **652** provides various outputs to light emitting

diode indicators **653**, a presence relay **656** for indicating the presence of an object, an RS 232 computer interface **657** and to a heater relay **666** contained within the power supply **336**. The microprocessor **652** receives additional inputs from a temperature sensor **651** and a real time clock **654**. The range/processor section **634** preferably also includes a battery backup circuit **658**.

The power supply section **636** includes an EMI/surge protection circuit **662** for a power supply **664** operated by 110 volt line current. The power supply circuit includes a heater relay **666** controlled by the microprocessor **652**, as discussed above, and receiving 110 volts line power. The heater relay is coupled to the window **320**, to maintain the temperature of the window **320** constant for varying ambient conditions.

For operation of the sensor **600**, in a vehicle-detection configuration reference is again made to FIGS. 14 and 15. The sensor **600** is at a height H above the highway **102**, and is displaced at an angle Theta **627** so as to be pointed toward the sensing area **108** defined by the beam separation W and the beam length L, and which is located a range distance R between the sensor **600** and the area **108**. In accordance with the discussion above with respect to the electrical-optical assembly **628**, the sensor **600** transmits two separate beams **609** and **611** (described as forward beam **106** and backward beam **110** with earlier description of sensor **100** and FIG. 1) which fall upon the area **108** defined by the length L and the width W. As illustrated again with reference to FIG. 15, when the vehicle **104** is positioned within the area **108**, by way of example, a portion **609A** of the radiated energy in beam **609** will be scattered from the vehicle **104** and away from the sensor **600**, while a portion **609B** is reflected back toward the

sensor **600** for detection by receiver section **632**, as earlier described.

As a result of the above description, it is thus understood that the microprocessor **652** using the software and the various inputs from the electrical-optical assembly first measures the range to the road; if the range falls below a predetermined threshold, the microprocessor signals that a vehicle **104** is present by closing the presence relay **656**, earlier described with reference to FIG. 16. By way of example, the threshold is determined by calculating the minimum, maximum and average range to the highway **102** for 100 discrete measurements. The maximum error is then calculated by subtracting the average from the maximum range measurement and the minimum from the average range measurement. The threshold is then set to the maximum error. The microprocessor **652** utilizing the software, to a certain degree classifies the vehicle **104** detected (as, for example, an automobile, a truck or a motorcycle) by examining the amount of range change, it being understood that a truck produces a much larger range change than an automobile, and a motorcycle a much smaller range change. The software keeps an accurate count of vehicles by classification for a predetermined period (for example, 24 hours) and in one example maintains a count of vehicle types for each hour of the day in order to provide a user flow rate.

The microprocessor **652** and the associated software also calculates the vehicle speed in the manner described above, by calculating the time each vehicle takes to pass between the two beams **609**, **611**. Specifically, the microprocessor **652** utilizes a microsecond time increment, and is reset to zero when the first beam **609** detects the presence of the vehicle **104**, and is read when the vehicle **104** is detected by

the second beam. The software then automatically calculates the distance between the two beams **609**, **611** by applying the law of cosines to the triangle formed by the two beams and the distance between them at the level of the highway **102**, as illustrated again with reference to FIG. 14. The speed is then calculated by taking the distance between the beams and dividing it by the time the vehicle takes to travel that distance.

The sensor **600** can also be utilized to ascertain the existence of poor highway visibility conditions, which is useful in providing a warning to drivers to slow down because of dangerous visibility conditions. The amplitude of the return signal received by the vehicle sensor is proportional to the atmospheric transmittance (visibility). Analysis has shown that the sensor can detect vehicles until heavy fog or rainfall reduces the visibility range to 18 m. Corresponding to the change in visibility from clear day to foggy conditions, the received signal power decreases by a factor of 22. Thus, a measurement of the return-signal amplitude can be used to ascertain the existence of poor highway visibility conditions. If the microprocessor **652** senses a return-signal level from the roadway below a certain preselected threshold, then the software can initiate an output through the interface **657** to an appropriate visibility warning signal.

It has been found that the sensor **100** achieved a detection percentage of 99.4%, and measured speed with an accuracy equal to or greater than that of conventional radar guns used for traffic enforcement purposes. The system also provided two dimensional vehicle range and intensity profiles. It was observed that the vehicles were accurately profiled, even in the area of the windshields where the intensity of the return signal was quite low, demonstrating the efficacy of the

intensity-dependent range correction in mitigating the effect of timing walk on range measurements at low return-pulse amplitudes.

Again with reference to FIG. 1, the present invention provides high resolution in both transverse axis (multiple forward cross scans **106** and multiple backward cross scans **110** of the lanes **114**) and longitudinal axis (collection of a multiplicity of ranges within the scans **106, 110** along the vehicle **104, 104a** passing in the lane **22**) to provide the three dimensional profile **128,** by way of example, of the vehicle **104.** This is true whether a single or dual transmitter and receiver sets are used to create the beam scanned coverage **116,** earlier described with reference to FIGS. 1 and 2. As described, one preferred embodiment comprises a first transmitter/receiver pair for coverage of a thirty degree beam with a second pair for a second thirty degree coverage, each positioned to provide the complete sixty degree coverage herein described, by way of example. With reference again to FIG. 17, the sensor **100** is mounted above the highway **102** over the center lane **115,** as earlier described, or over a lane of interest depending on the desired use. By way of example, when a single beam **140** is pointed in the direction of a scanned angle alpha **142,** the sensor **100** makes a measurement of the highway **102** for that particular angle alpha one, for example, alpha **142a.** When the beam **140** is pointed in the direction alpha two **142b,** it makes the next measurement. This continues at regular angle spacing until measurements are completed across the complete traffic lanes, again for a single transmitter/receiver system or the sensor **100,** described with reference to FIGS. 1 and 2, for multiple lanes. By way of example, with a total scan angle of 30 degrees, for each transmitter/receiver and one degree

between measurements, the maximum separation between measurements on the highway **102** can be calculated as approximately 25 ft (tan 15 degrees - tan 14 degrees) = .465 ft or 5.6 inches. When the vehicle **104** is present, the distances or ranges to the points **136** on the surface of the vehicle **104** are measured. These ranges **144** or measured distances at the various scan angles **142** are then used in generating the vehicle profile **128** as illustrated in FIG. 10. The profile **128** is formed by generating measured points **136** above the highway **102** by geometric transformation well known in the art.

To continue with the above example, one embodiment comprises the 12 sided mirror **303** rotating so as to provide a scan rate of 720 scan/sec. If the vehicle **104** is traveling at a rate of 100 mph or 146.7 feet/sec, the scan separation distance **124** would be equal to 146.7 ft/sec divided by 720 scans/sec or 2.4 inches. For a vehicle **104** traveling at 50 mph, the separation distance **124** is less than 1.25 inches. Such separation distances **124** provide detail sufficient to provide a three dimensional profile for accurately classifying the vehicle **104**.

As illustrated with reference again to FIG. 1, the sensor **100** has the forward beam **106** tilted at 5 degrees toward oncoming traffic and the backward beam tilted at 5 degrees away from oncoming traffic traveling in the lane **22**. As described earlier, the laser beam transmitter **200** is triggered at each one degree (angle alpha **142**) increment of the 30 degree scan portion of the complete scanned beams **106, 110**. Again with reference to FIG. 1, a vehicle **104** will intercept the forward scanned beam **106** and then the vehicle **104a** will intercept the backward scanned beam **110** and the time between

interceptions is calculated. The distance between the forward **106** and backward **110** beams on the highway **102** is equal to 2 X 25 X tan 5 degrees or 4.37 feet. At 100 mph and a scan rate of 720 scans/sec as discussed in the example considered, there are 21.47 scans between the interception of the two scanned beams **106, 110**. Using timing signals from the generated laser pulses, as described earlier with reference to FIG. 8, the maximum timing error possible is one scan period and does not exceed 5% at 100 mph and 2.5% at 50 mph. The length measurement accuracy of the vehicle profile **128** is a function of speed and is therefore within 5% when the vehicle **104** is traveling at 100 mph and improves linearly as the speed decreases.

Yet another embodiment for providing the forward **106** and backward **110** scanned beams is illustrated in FIG. 18 and again with reference to FIG. 8, and comprises the use of the nodding mirror **318** which changes from a first position **322** to a second position **324** to reflect the transmitted laser beams **105**, illustrated again with reference to FIGS. 3 and 8, as well as a corresponding returning reflected beam, off of facets **309** of the rotating polygon shaped mirror **303** having the facets **309** at the same inclination unlike the angled mirror facets **308** described earlier. As further illustrated with reference to FIG. 8, the bi-stable positioner **320** directs the nodding mirror **318** into its first **322** and second **324** positions. In the mirror system **300** embodiment illustrated in FIG. 8, a twelve sided polygon is used for the rotating mirror **303**. In this embodiment, the processor **502** provides a signal **326** to the bi-stable positioner **320** which moves the nodding mirror **318** onto every other mirror facet **309**. As discussed, the functional flow of the electronics generally follows that as herein described. It will be appreciated that

the sensor **100** of present invention includes an optical/mechanical multiplexing with the use of the nodding mirror **318**, by way of example, rather than the analog multiplexing described with reference to the earlier developed sensor **600**.

In yet another embodiment of the present invention, and as illustrated with reference to FIG. 19, forward **106** and backward **110** scam beams are provided using two laser transmitters **200a**, **200b** as well as two receivers **400a**, **400b** as illustrated in FIG. 19. It will be obvious to one of skill in the art, that the electronics of such an embodiment can be as earlier described with reference to sensor **100**. In the embodiment illustrated with reference to FIG. 19, a planar mirror **328** is rotated by a motor **330** whose revolutions are monitored by an encoder **332** and counter **334** for providing angle data signals **336** to the processor **502**. As functionally illustrated again with reference to FIG. 19, the forward beam **106** and backward beam **110** are positioned at predetermined angles as described earlier by directing the transmitter/ receiver pairs at appropriate angles. The rotating mirror **328** scans through a full cycle but only data applicable to the scanned beam positions of interest will be processed.

Before considering an appropriate software for the sensors herein described, consider, as illustrated with reference to FIG. 20, an allocation of measurements taken by the sensor **100** and measurements derived by the sensor **100**, as direct functions **150** and derived functions **160**, respectively. To summarize and highlight operation of the sensor **100**, consider that a "profiler" compares consecutive range samples and records the profile trends **162**. Three trends are recognized: rising edges, falling edges, and plateaus, which are defined as a minimum number of consecutive samples at the

same range. To reduce the number of trends in the profile, the range resolution is reduced to 1 foot such that all ranges are rounded-off to the nearest foot. The profiler builds a data structure that contains the profile trends. Each record in the data structure contains the trend type, the length of the trend, and the height of the trend. The data structure is then used by the vehicle classifier **164** to calculate the classification features. The profile trends **162** are also output to the central processor along with a time-tag to be used for the link travel-time calculation

Vehicle classification **164** is accomplished by analyzing the range data recorded for a vehicle and matching the resultant profile to a defined set of rules. There are seven features that are used to classify a vehicle. The first feature that is calculated is the total length of the vehicle **166**, which is derived from the length of each profile trend. Next, the height **168** of each plateau is compared to find the maximum plateau height. This feature will be used as the height of the vehicle. The average width **170** of the vehicle is only available if 3-dimensional data are being used. The ratio of plateau lengths to total length is used to determine how aerodynamic the vehicle is. The percentage of the vehicle above a 5 foot threshold and the height and length of the last plateau are features used for sub-classification.

If the speed of a vehicle falls below 1 mph, implying that the vehicle may have come to a complete stop below the sensor, all classification features that use length in their calculations have to be avoided. However, the maximum plateau height and average width are still available and are valid for vehicle classification.

A preferred embodiment of the software useful in connection with the sensor system and method of earlier

patented invention is illustrated in flow charts and discussed in detail in the above reference patents. It will of course be understood that the software is loaded in an object code format into the microprocessor **500**, and is designed to control the electrical-optical assembly of the sensor **100** in order to detect the presence of objects and to provide certain desirable outputs representative of the object, including for example, the speed with which the object moves through the area being sensed, the size and shape of the object, its classification and perhaps other characteristics. In one specific form, and as earlier described, the sensor **100** has utility as a vehicle sensor for mounting in an overhead configuration in order to detect the presence of vehicles passing through an area--such as a portion of a roadway at an intersection--to identify the presence of a vehicle, classify the vehicle as either an automobile, truck or motorcycle, count the number of vehicles passing through the intersection and calculate the speed of each vehicle and the flow rate of all of the vehicles. The software was specifically configured to meet the needs of a particular application, herein described by way of example.

As described with reference to FIGS. 21 through 27, software operates to find the range to the road. The software then sets up the receiver **400** to detect the return beam **106b**, **110b**, and the range and return-signal intensity is read; the range and intensity reading is then toggled between the two beams **106**, **110**. Following the reading of the range and intensity from each of the two beams **106**, **110**, any necessary offset is added to the range based on the intensity to correct timing walk as discussed earlier. The change in the range (i.e., the road distance minus the distance to any object detected) is calculated. If the resulting calculation is

greater than the vehicle threshold, then a vehicle pulse counter is tested to determine if there have been 16 consecutive pulses above the vehicle threshold; if the calculation is less than the vehicle threshold, then another sequence of steps is initiated to reset the vehicle pulse counter and thereby toggle between the beams **106**, **110**. Various resets and adjustments are made including the calculation of the distance between the two beams, the calculation of the average range to the road, and the minimum/maximum range to the road.

If the road pulse counter is reset, an inquiry is made as to whether the vehicle has already been detected; if the answer is affirmative, then an inquiry is made to determine if the change in range determined earlier is greater than the truck threshold in order to complete a truck-detection sequence. On the other hand, if the inquiry is negative, then the vehicle presence relay is set, a vehicle pulse counter is incremented, and a velocity timer is started for purposes of determining the speed of the vehicle passing through the area being sensed.

One embodiment of the software useful in connection with the sensor **100** and method of the present invention is illustrated in flow chart form in FIGS. 22 through 28 with portions of the software depicted in each of those figures being arbitrarily designated by reference numerals. It will of course be understood that the software is loaded in an object code format and is designed to control the sensor **100** electrical, optical and mechanical components as herein earlier described. In one specific form, the sensor **100** has utility for determining the speed of a vehicle and determining its vehicle classification through comparison of its three dimensional profile with known vehicles establish in a database. By way of example, the software modeling of

FIGS. 21 through 27 has been specifically configured for these purposes.

Referring first to FIG. 21, the microcontroller software scan **720** in the forward scanned beam **106**. Fig. 22 further illustrates that this scan **720** is started **722** and the start time recorded **724**. A range and intensity are measured **726** as described earlier. The intensity value is used to calculate an offset to be added to the range in order to correct for time walk **728**. As described with reference to FIG. 17, the current scan angle **142** is determined from the motor encoder within the mirror electronics and the information used to calculate a cosine correction for the range **732** as earlier discussed. Ranges are accumulated **734** and recalculated at the various predetermined angle increments for the predetermined scan **736** and the end of the scan time is recorded **738**. Once the scan cycle described is completed, it is determined whether a vehicle has been detected **740** by comparing ranges measured with sample ranges for database vehicles **742** and determining how such ranges compare **744** (refer to FIG. 23). If a vehicle has previously been detected **746** data is sent to the microprocessor for classification **748**, start times are recorded **750** and vehicle detection indicated **752** if a vehicle was not previously detected. Co-pending software uses these **750** and **752** steps and has further detail included in its specification for a reference. A range calibration is run **754** and then the process begins for the backward scanned beam **756**. As illustrated in FIG. 24, the backward scan begins **758** and the start time recorded **760**. The process is as described in steps **762** through **774** and is as described for the forward scan in steps **722** through **738** and as described for the forward scan

in **742** through **754** as **776** through **784** (see FIG. 25). Except in the backward scan processing, a stop time is recorded **786** if a vehicle was nor previously detected. With the start time from the vehicle crossing the forward beam and stop time when the vehicle crosses the backward beam, a speed is calculated using the time period determined and the known distance between the beams **106, 110**. Once the backward scan is completed for all the predetermined angles **28**, the forward scan is then again begun **790**.

The range processor **502**, completing its tasks as described, the data processor **504** performs its tasks which are illustrated in the flow charts of FIGS. 26 and 27. A data packet from the microcontroller **504** containing range, intensity, angle and time data **792** in FIG. 27, is processed through a median filter for smoothing over each scan profile **794**. A feature set for the classification is calculated **796** for comparing the features of the vehicle detected to the features of vehicles contained in a vehicle database library **798** and vehicle speed and classification is provided as an output **800**. In calculating a feature set for the detected vehicle (**796** of FIG. 26), each scan is assembled into an image forming a three dimensional profile of the vehicle (**802** of FIG 27) as illustrated earlier with reference to FIG. 10. Features used in the calculation are calculated **804** and compared as discussed **798** and an output provided **800**. The features compared are not limited to but include vehicle surface area **806**, length of the vehicle **808**, width of the vehicle **810**, height of the vehicle **812**, a ratio of cross-sectional surface area to total surface area **814** and intensity **792**.

Further improvement is now described with reference to the present invention, described herein for sensor **100**, by way of example. Consider the effects on sensor measurements when using a generally flat reflective surface, such as in the facets of a rotating polygon scanner, to scan a pair of beams onto the surface of a generally flat roadway. With such an arrangement, geometric constraints cause the scanned beams to take on a "bow-tie" shape as projected on the roadway, as opposed to a parallel scanned line shape across the roadway. Over relatively small scanning angles typically used for one or two traffic lanes, a negligible effect on vehicle classification results. However, for large scanning angles, such as 60°, by way of example as is used in multi-lane systems scanning typically four-to-six traffic lanes, the bow-tie effect can add unwanted error in the accuracy of desired measurements. As a result, improvements to the above described sensor include consideration for such geometric scanning effects.

As herein earlier described, the sensor **100** used in both Autosense II and III commercial versions, employ rotating polygon mirror of the type described with reference to system **300** for scanning a pair of lines or laser beams **106, 110** having an angular separation of 10°, onto the flat surface of a roadway or highway **102**, as earlier described with reference to FIG.1, by way of example. The geometry of the situation forces the projected line or scanned beams **106, 110** to have the shape of a bow tie, as earlier described. This is of little consequence over the 30° of scan covered by way of example, for a sensor as described for embodiment of an Autosense II for a small few lanes of traffic. However, the effect is not negligible over the 60° scan of an Autosense III, that is intended for use in higher multiples

of traffic lanes. Since the measurement of speed by Autosense III depends upon beam separation, it was necessary to determine the variation in beam separation along the scan path to ensure an improved accuracy of the collected data such as for speed data. By way of example, and with reference again to FIG. 4, the sensor **100**, referred to commercially and herein as Autosense III includes a structure and geometry as earlier described. The polygon mirror **302** rotates clockwise within a plane of rotation being a plane of the paper for descriptive purposes. With reference again to FIG. 5, the polygon facets **308** are tilted ±2.5° to cause the beams **106, 110** described with reference to FIG. 1, to scan at ±5° with respect to the plane of rotation. The incident angle is the angle that the beam makes with the perpendicular to the polygon facet **308**.

Analysis has shown that there were actually two factors causing the beam to scan in a nonlinear or other than straight line across a surface such as a surface of the highway **102**, or a wall used in an experimental setup herein described by way of example with reference to FIGS. 28-33. A first effect factor, dubbed the "smiley face", occurs when a scan line which is tilted out of the plane of rotation hits a flat surface. At the ends of the scan, the distance to the surface is greater than it is directly in front of the sensor. Therefore, the beam has a further distance to travel and consequently ends up farther away from the plane of rotation. By way of further example, in a round room having cylindrical shaped walls, with the sensor in the middle of the room, a straight line would be scanned on the wall, but on a flat wall, by way of example, the "smiley face" results. Now recognized, this is not a difficult problem to overcome.

However, it is not the only factor affecting the projected scan line.

A second factor changed not only the position of the scan on the wall, but also the tilt angle which the beam made as it exited the sensor. We have called this the incident-angle factor. Depending on the geometry inside the sensor **100**, the laser beams hit the polygon facets **308** at different incident angles. Since the polygon facets **308** are tilted with respect to the plane of rotation, the beam should reflect off the facet at twice the tilt angle. This would happen if the incident angle in the plane of rotation is zero degrees (i.e., along the axis perpendicular to the face). However, as the incident angle increases, the degree at which the beam tilts out of the plane of rotation lessens. In fact, as the incident angle approaches 90° of the out-of-plane beam angle approaches zero degrees.

As will now be described with reference to FIGS. 28-33, angular separation measurements were made by pointing a sensor at a wall and tracing the path the beams made as they hit the wall. A helium-neon laser was utilized to provide a visible laser beam path through the system. The geometry of the setup was measured, and the separation angle between the two beams was computed.

A wall **900** was constructed so that it was perpendicular to an axis **902** of alignment holes **904** of an optical table **906** upon which the sensor sat and perpendicular to the plane of the optical table. This was achieved by marking the spot on the wall in the plane of the table aligned down an axis of alignment holes (this was accomplished by simply aligning a laser with the alignment holes and marking its spot on the wall). Then, to orient the wall **900** perpendicular to an axis of alignment holes on the optical table, marks **908** were

placed equidistant to the left and right of the center mark on the wall. The distance **910** from each of these marks back to a point on the chosen axis of alignment holes must be the same for the wall to be perpendicular to that axis. The same procedure was repeated in the vertical direction to orient the wall perpendicular to the plane of the optical table as illustrated with reference again to FIGS. 28 and 29. This ensured that inaccuracies in the physical lab setup (i.e., floor not level, optical table not in same plane as the floor, etc.) would not affect the measurements.

During the test, the sensor **100**, an Autosense III unit (with only the polygon and mirrors mounted on it) was fixed to the table utilizing the alignment holes so that the central axis of the sensor aligned with the axis of the optical table pointed towards the wall. The base of the sensor was parallel to the surface of the table. The helium-neon laser was attached to the optical table so that its laser beam was parallel to the plane of the table and aligned parallel to the axis of alignment holes down the table pointed towards the center of the mirror that reflects the beam onto the polygon facets. The reflecting mirrors were aligned to be within ±5 minutes of their locations designed for the sensor **100**.

After sensor alignment, the polygon was spun-up using a motor, and the scan lines projected onto the wall **900** for the +5° beam and the -5° beam were traced onto paper. The test was repeated for the laser beam on the opposite side of the sensor. After all the beams were traced on the wall **900**, the laser beam was directed straight at the wall for the entire range of scan angles. The line this beam made as it intersected the wall was also traced as a reference of where the plane of the optical table intersected the wall. A

depiction of how the traces appeared as drawn on the wall is illustrated with reference to FIG. 30. Along with the four polygon-scanned traces and table-plane trace were the marks at the axis of the originating beams.

The dependence of the angular separation of the laser beams from the sensor **100** upon angle of incidence in the x-y plane was determined by analyzing the geometry that results when the law of reflection is applied to a laser beam incident upon the tilted facet of the polygon. The coordinate system shown in FIG. 31 was used, where:

1. (0,0,0) is the point **912** where the beam **914** hits the facet **308**.
2. The Y-axis is in the plane of the facet.
3. The beam originates in the x-y plane and travels in the x-y plane towards the facet at point (0,0,0).
4. Tilt Angle **916** is the angle in the x-z plane between the +Z-axis and the plane **918** which contains the facet **308** as it rotates about the Y-axis (a tilt angle of 0° would indicate that the plane which contains the facet is the y-z plane).
5. Incident Angle **918** in the x-y plane is the angle from the +X-axis to the beam in the x-y plane (remember the beam originates in the x-y plane).

The geometry consistent with the reflection of a laser beam from a tilted polygon facet **308** in the sensor **100** is illustrated with reference to FIG. 32, where line FA is perpendicular to the polygon facet, plane defined by CAB is the plane of incidence, plane DAB is in the x-y plane, angle FAB is the angle of incidence (in the plane of incidence, and not in the x-y plane), angle FAE is the facet tilt angle **916**, and angle FAB equals angle CAF by the law of

reflection. The angle CAD, which is the reflected beam tilt angle, and angle DAE, which is the reflected beam scan angle (in the x-y plane) are to be determined.

If we call the incident angle in the x-y plane "ι", the facet tilt angle "τ", the reflected-beam tilt angle "T", and the reflected-beam scan angle "S", then

$$T = \sin^{-1}\left[\sin\left(\cos^{-1}\left[\frac{\tan(\iota)}{\sqrt{\tan^2(\tau)+\tan^2(\iota)}}\right]\right) \times \frac{\sin\left(2\times\cos^{-1}\left[\cos(\tau)\times\cos(\iota)\right]\right)}{\sin\left(\cos^{-1}\left[\frac{\tan^2(\iota)\times\cos(\iota)}{\sqrt{\tan^2(\tau)+\tan^2(\iota)}}\right]\right)}\right]$$

$$S = \sin^{-1}\left(\frac{\frac{\tan(\iota)}{\sqrt{\tan^2(\tau)+\tan^2(\iota)}}\times\sin\left(2\times\cos^{-1}\left[\cos(\tau)\times\cos(\iota)\right]\right)}{\cos(\angle CAD)\times\sin\left(\cos^{-1}\left[\frac{\tan^2(\iota)\times\cos(\iota)}{\sqrt{\tan^2(\tau)+\tan^2(\iota)}}\right]\right)}\times\sin(90-\iota)\right)-\iota$$

It can be noted that for the working domain of the sensor **100** such as that embodiment of an Autosense III, sensor of ±2.5° tilt angle "τ" and 7.5° - 37.5° incident angle in the x-y plane "ι" , the reflected-beam tilt angle "T" can be approximated using the following formula:

$$T = \tan^{-1}\left[\tan(\tau)\times\cos(\iota)\right]$$

and the reflected-beam scan angle "S" can be approximated by the incident angle in the x-y plane "ι".

The incident angle in the x-y plan for this configuration was computed for each scan angle in the operating range of the sensor **100**. Utilizing the derived formulas for the reflected-beam scan angle and reflected-beam tilt angle, the measured values were plotted to gauge the accuracy of the prediction and are as illustrated, by way of example, with reference to FIG. 33. The lines **914** are

predicted values and the thin lines **916** are the measured values.

The measured values are well within ±0.1° of the predicted values. It has been determined that if the inter-beam angle is known to within ±0.1°, the speed measurement accuracy of the sensor will be within ±1.36 mph at 60 mph. In fact, the actual error measured is within ±0.04°, which would produce a speed measurement accurate to ±0.5 mph at 60 mph. The formulas for predicting the angle between the two beams at any point across the scan of an Autosense III, sensor **100**, by way of example, were used to build a look-up-table that is used by the speed-calculation algorithm, earlier described.

As described earlier, the sensor **100** used in vehicle detection is useful in determining and recording other highway conditions such as visibility.

Many modifications and other embodiments of the invention will come to the mind of one skilled in the art having the benefit of the teachings presented in the foregoing descriptions and the associated drawings. Therefore, it is to be understood that the invention is not to be limited to the specific embodiments disclosed, and that modifications and alternate embodiments are intended to be included within the scope of the appended claims.

What is claimed is:

1. A sensor useful in determining the shape of a vehicle, the sensor comprising:

multiple laser rangefinder means for providing multiple laser beams and range measurements from the sensor to multiple points on a vehicle when the vehicle travels within any of multiple traffic lanes being viewed by the sensor, the multiple laser rangefinder means providing a range measurement associated with a corresponding sensor angle for each of the beams;

scanning means for scanning the multiple laser beams within a first transverse plane and a second transverse plane generally divergent from each other and each plane generally orthogonal to a direction of travel for the vehicle, the scanning means communicating with each of the multiple laser rangefinder means for providing scanning of the beams within the first and second planes extending across multiple lanes of traffic, the determining a range for a corresponding point on the vehicle within the transverse plane, the scanning means providing means for determining the range and a corresponding sensor angle for each point within the scanning plane;

deflecting means cooperating with the scanning means for deflecting the scanned beam from a first position to a second position, the first and second positions defining a forward beam and a backward beam through which beams the vehicle travels; and

means for processing the ranges, corresponding angles, and interception times for the vehicle receiving the first and second beams, the processing means including beam scanning compensation for providing a vehicle image profile representative of the vehicle.

2. A sensor useful in determining the shape of vehicles traveling over multiple adjacent lanes of a highway, the sensor comprising:

a housing for positioning above a highway having multiple lanes for receiving vehicles traveling thereover;

first and second laser transmitters carried by the housing, each laser transmitter transmitting a series of radiation pulses forming first and second beams respectively, the first and second transmitters each providing a trigger signal indicating the transmitting of each pulse within the series;

a beam scanner carried by the housing, the beam scanner having multiple reflective facets positioned for receiving the first and second transmitted beams and directing the beams toward the highway, the reflective facets intercepting the beams at varying incident angles for reflecting the beams through the varying angles and scanning the beams transversely across the highway, the scanned beams cooperating for providing a scan extending transversely across the multiple lanes, the reflective facets further arranged such that adjacent facets receiving the transmitted beams have differing orientations for alternately reflecting the beam from a first facet into a forward scanned beam and from a second facet into a rearward scanned beam, the forward and rearward scanned beams longitudinally divergent from each other, the beam scanner communicating with the first and second transmitters for providing an orientation signal indicating a direction of beam propagation for each transmitted pulse within the beam;

first and second laser receivers carried by the housing, each laser receiver receiving reflected first and second beams including pulses reflected back from the highway

and vehicle for the respectively transmitted pulses of the first and second transmitted beam, the first and second receivers providing a return pulse signal indicating the receipt of each reflected portion of the transmitted pulse within the series; and

a processor carried by the housing for processing the signals from the transmitters, receivers and scanner for providing range measurements from the sensor to the highway, from the sensor to the vehicle, corresponding angles for each range measurement, and a time for the vehicle to cross the forward and rearward scanned beams, the processor including beam scanning compensation for providing vehicle information useful in classifying the vehicle.

3. The sensor according to Claim 2, wherein the beam scanner comprises a polygon rotating about a shaft, the polygon having the facets portioned continuously about the shaft for intercepting the transmitted beams, and wherein the first and second facets are adjacent facets positioned at an offset angle to each other for providing the forward and the rearward diverging beams.

4. The sensor according to Claim 3, wherein the offset angle is approximately ten degrees.

5. The sensor according to Claim 3, further comprising a shaft encoder engaging the shaft for providing a signal indicative of the shaft polygon orientation and thus the beam angle, the shaft encoder providing the orientation signal.

6. The sensor according to Claim 2, further comprising a folding mirror carried within the housing for

directing the beams from each of the transmitters and receivers to the beam scanner.

7. The sensor according to Claim 2, wherein each receiver comprises an optical detector for detection of the reflected beam, the optical detector providing the return pulse signal.

8. The sensor according to Claim 2, wherein the housing includes a light transmissive window for transmitting the beams therethrough, the window having a heater for maintaining a preselected temperature of the window during varying ambient conditions.

9. A sensor useful in determining the shape of vehicles traveling over multiple adjacent lanes of a highway, the sensor comprising:

first and second laser transmitters, each transmitting a series of radiation pulses forming first and second beams respectively, the first and second transmitters providing a trigger signal indicating the transmitting of each pulse within the series;

a beam scanner having multiple reflective facets positioned for receiving the first and second transmitted beams and directing the beams toward the highway, the reflective facets intercepting the beams at varying incident angles for reflecting the beams through the varying angles and scanning the beams transversely across the highway, the scanned beams cooperating for providing a scan extending transversely across the multiple lanes, the reflective facets further arranged such that alternating facets receiving the transmitted beams have differing orientations for alternately reflecting the beam from a first facet into a forward

reflected beam and from a second facet into a rearward reflected beam, the forward and rearward beams longitudinally divergent from each other, the beam scanner communicating with the first and second transmitters for providing an orientation signal indicating a propagation direction for each transmitted pulse;

first and second laser receivers, each laser receiver receiving reflected first and second beams having a portion of the respectively transmitted pulses of the first and second transmitted beam, the first and second receivers providing a return pulse signal indicating the receipt of each reflected portion of the transmitted pulse within the series; and

a processor for processing the signals from the transmitters, receivers and scanner for providing range measurements from the sensor to the highway, from the sensor to the vehicle, corresponding angles for each range measurement, and a time for the vehicle to cross the forward and rearward beams, the processor including beam scanning compensation for providing vehicle information useful in classifying the vehicle.

10. The sensor according to Claim 9, wherein the beam scanner comprises a polygon rotating about a shaft, the polygon having the facets portioned continuously about the shaft for intercepting the transmitted beams, and wherein the first and second facets are adjacent facets positioned at an offset angle to each other for providing the forward and the rearward diverging beams.

11. The sensor according to Claim 10, wherein the offset angle is approximately ten degrees.

12. The sensor according to Claim 10, further comprising a shaft encoder engaging the shaft for providing a signal indicative of the shaft polygon orientation and thus the beam angle, the shaft encoder providing the orientation signal.

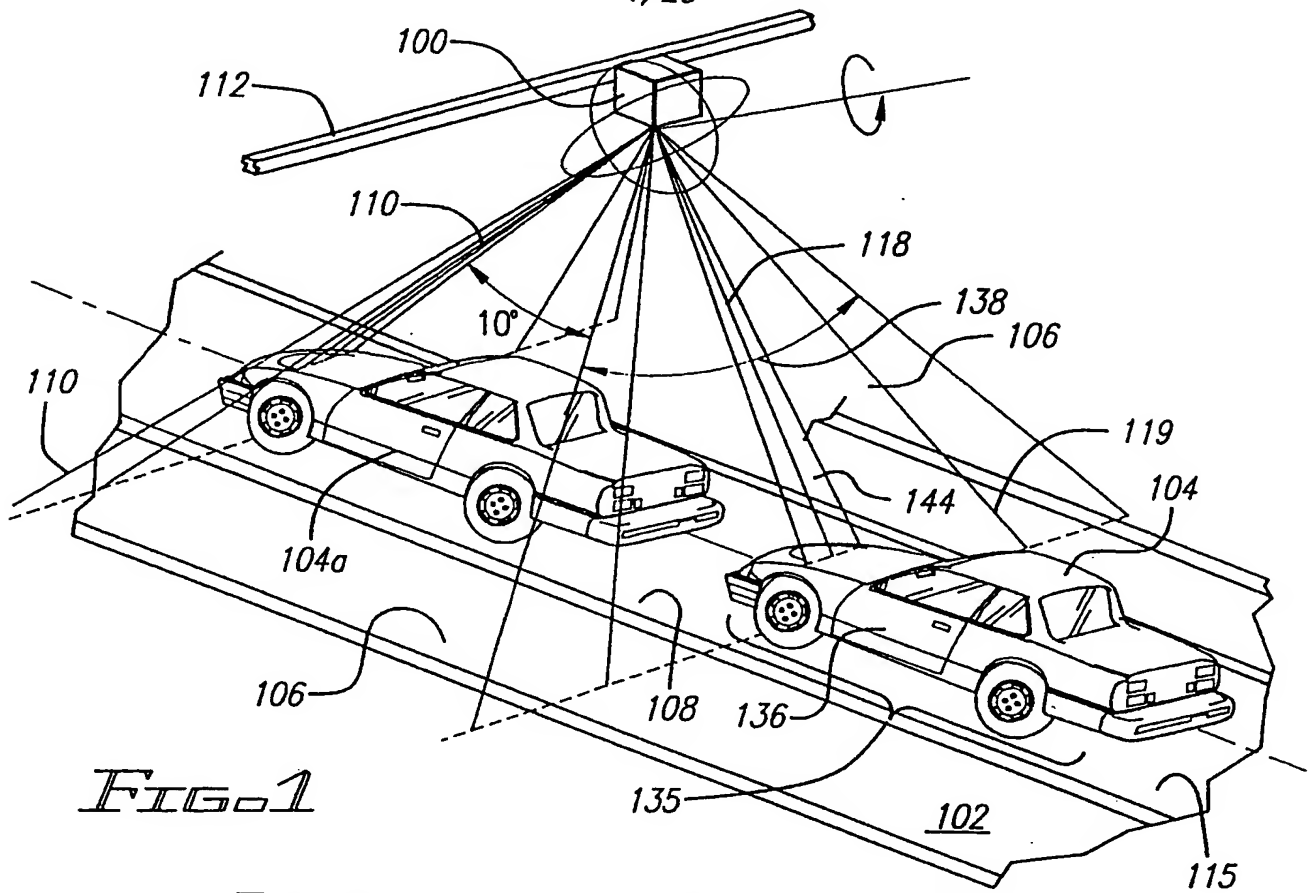

100
112
110
10°
118
138
106
110
119
144
104
104a
106
108
136
135
102
115

FIG. 1

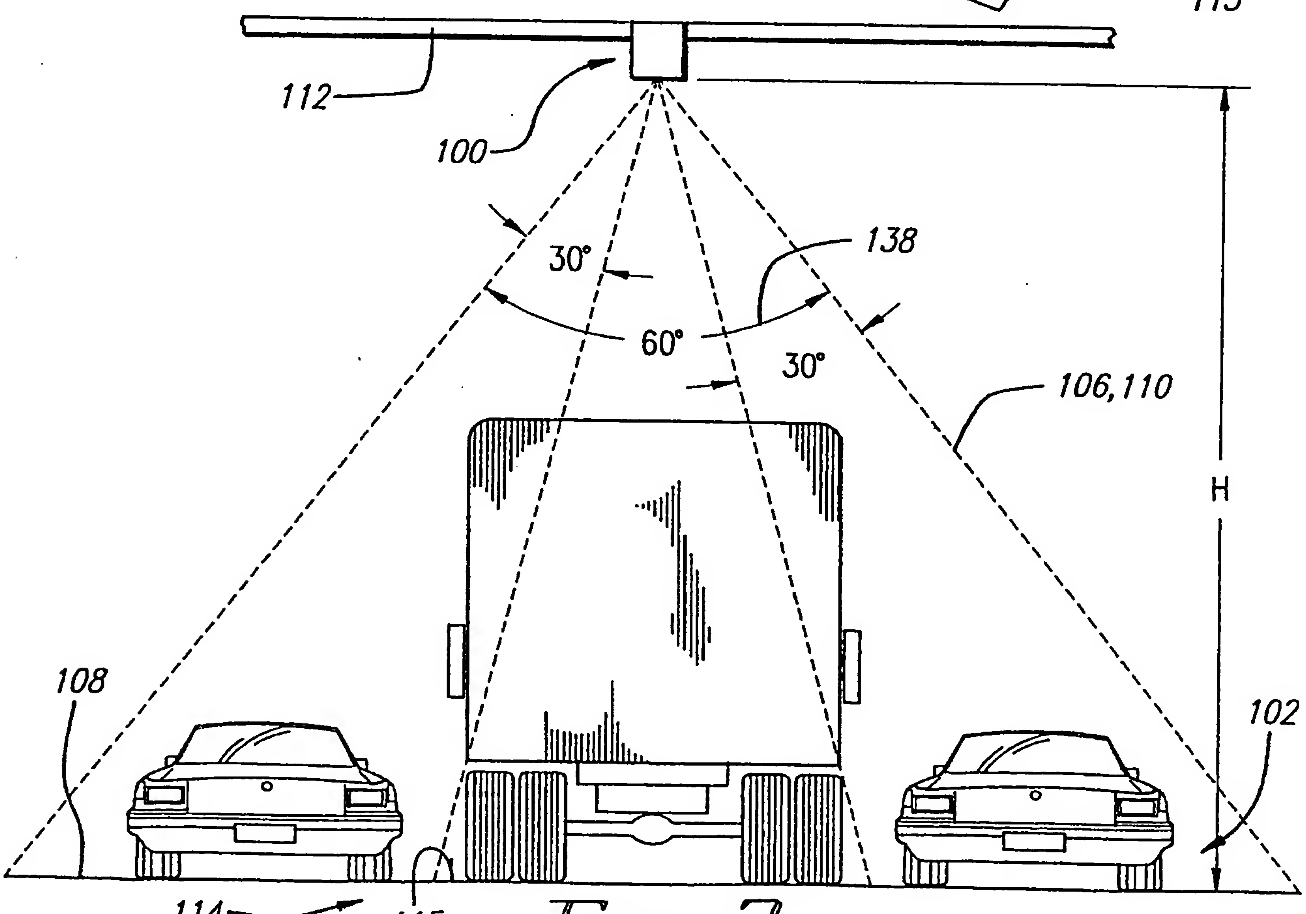

112
100
30°
138
60°
30°
106,110
H
108
102
114
115

FIG. 2

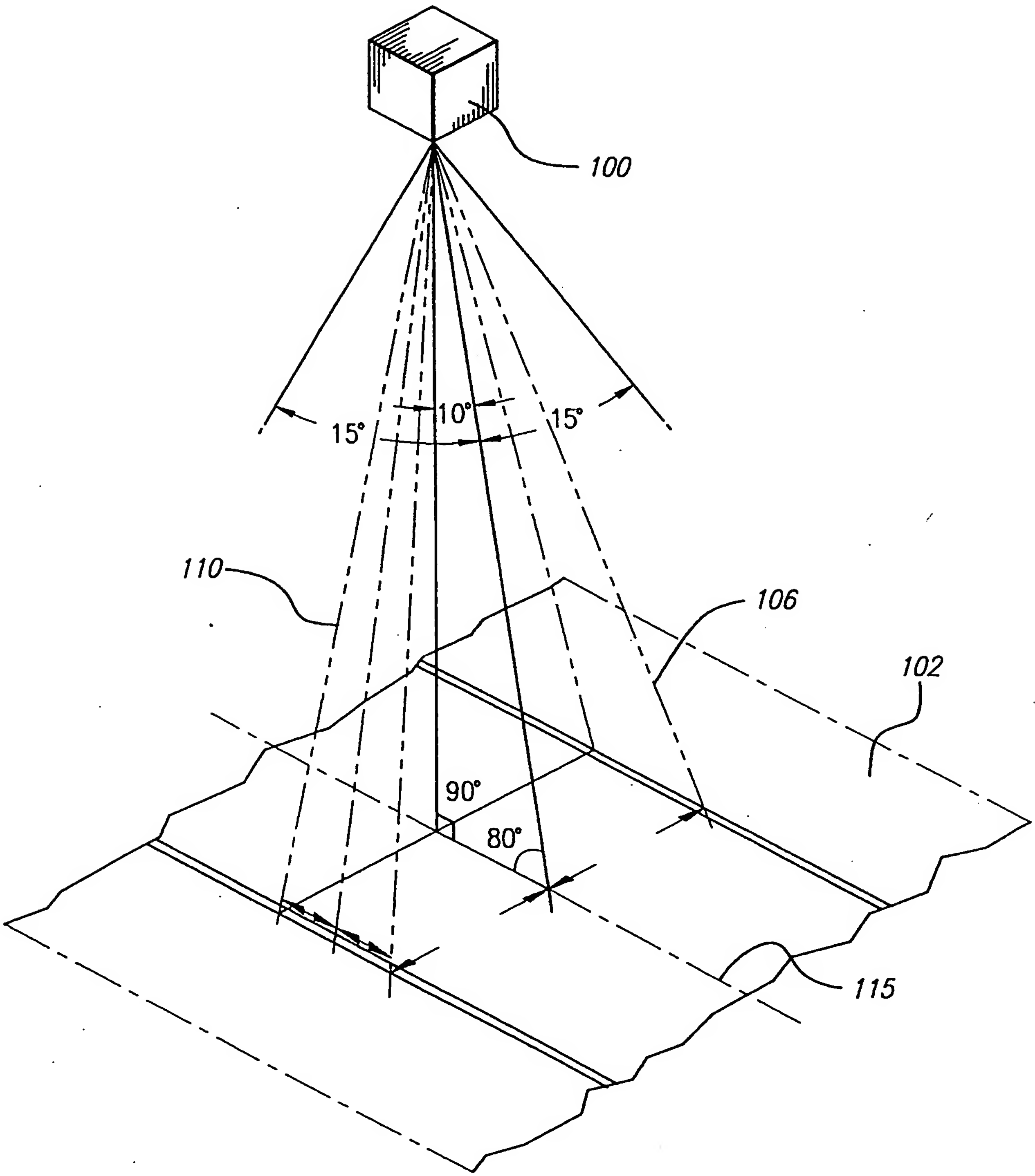


FIG. 2A

3/23

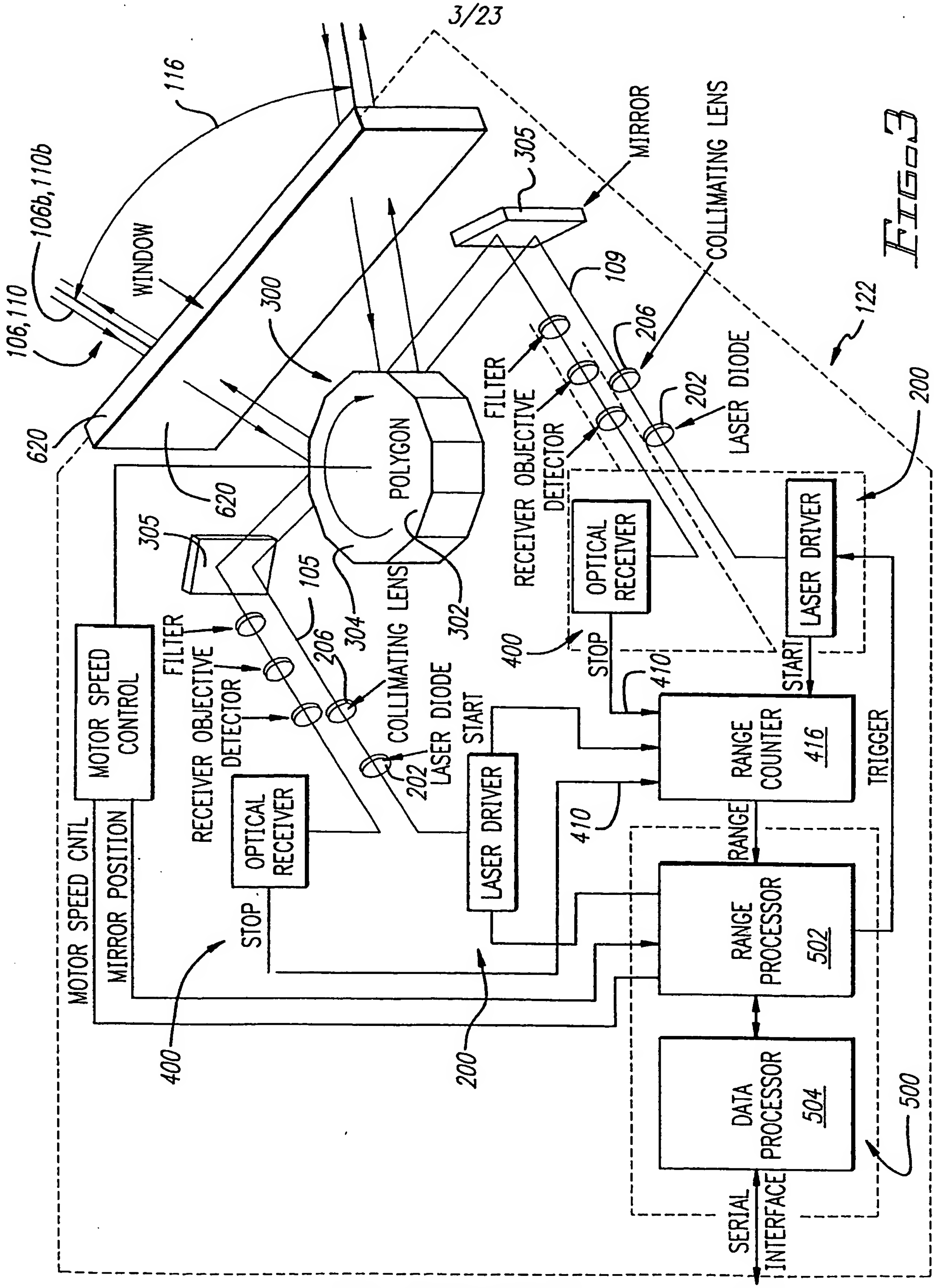

116
106b,110b
106,110
WINDOW
300
620
305
MIRROR
COLLIMATING LENS
109
206
122
FILTER
RECEIVER OBJECTIVE
DETECTOR
202
LASER DIODE
200
POLYGON
304
302
105
OPTICAL RECEIVER
LASER DRIVER
400
STOP
START
410
MOTOR SPEED CONTROL
RANGE COUNTER
416
TRIGGER
RANGE
RANGE PROCESSOR
502
DATA PROCESSOR
504
500
MOTOR SPEED CNTL
MIRROR POSITION
SERIAL INTERFACE
TO PC

FIG. 3

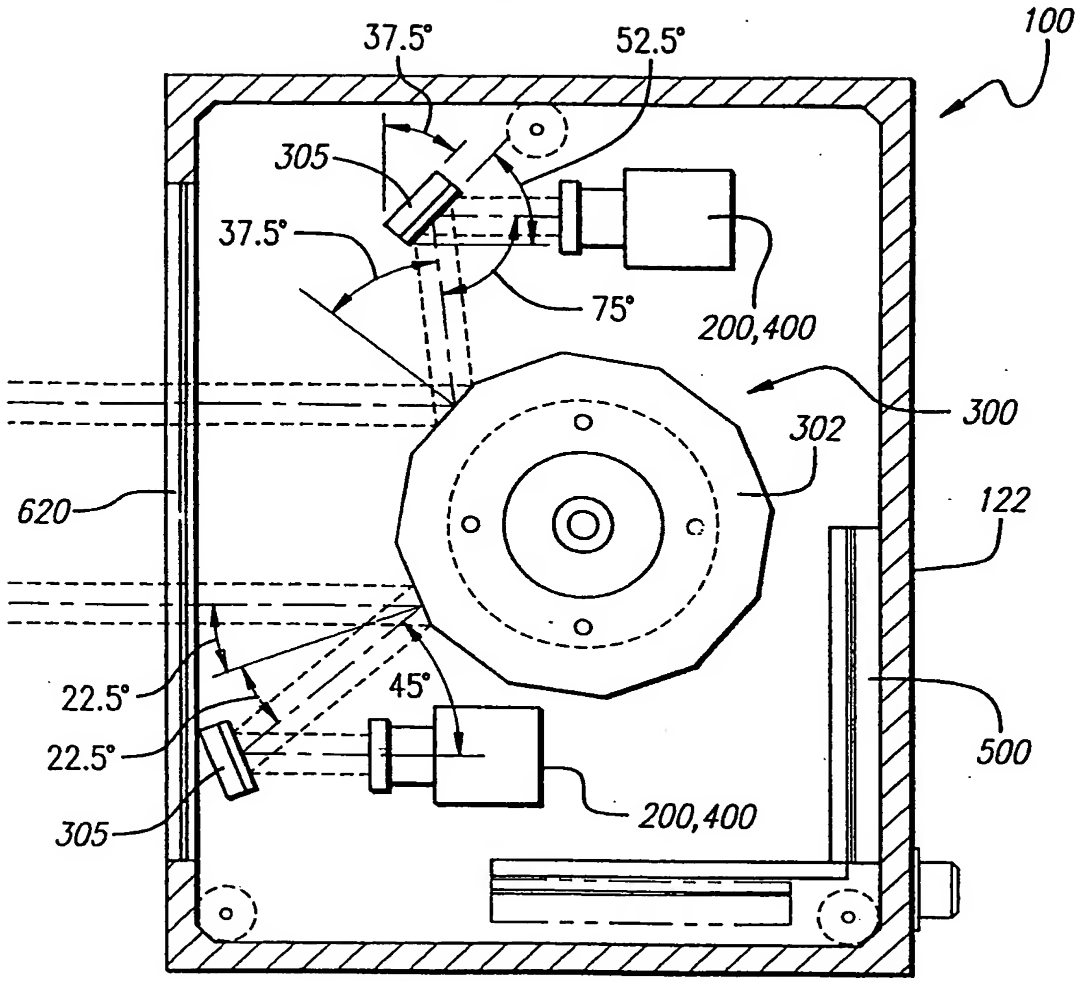

100
37.5°
52.5°
305
37.5°
75°
200,400
300
302
620
122
22.5°
22.5°
45°
500
305
200,400

FIG. 4

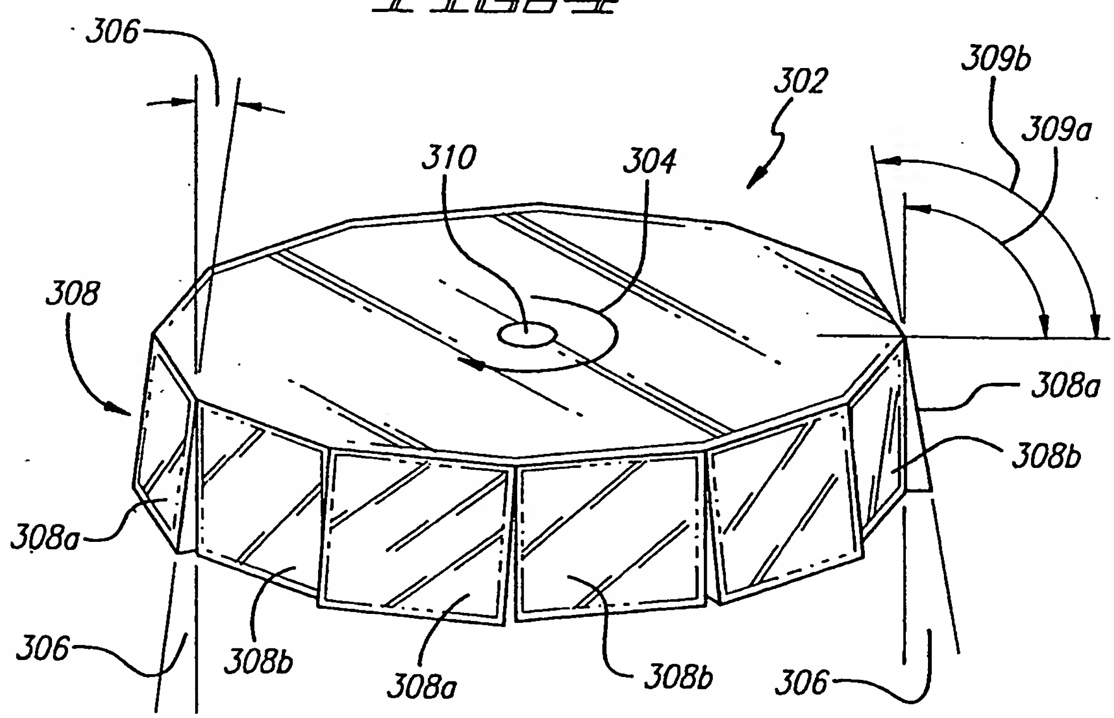

306
302
309b
309a
310
304
308
308a
308b
308a
306
308b
308a
308b
306

FIG. 5

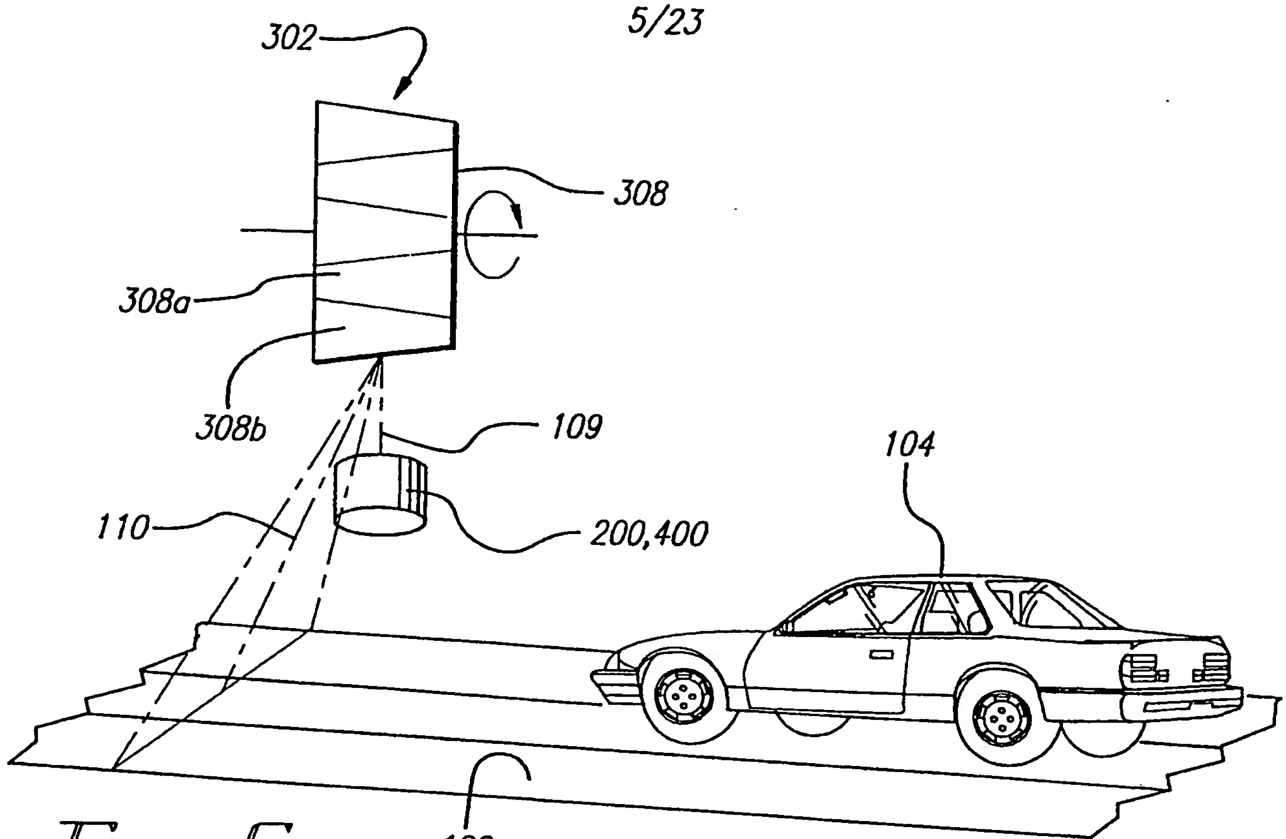

302
308
308a
308b
109
104
110
200,400
102

FIG. 6

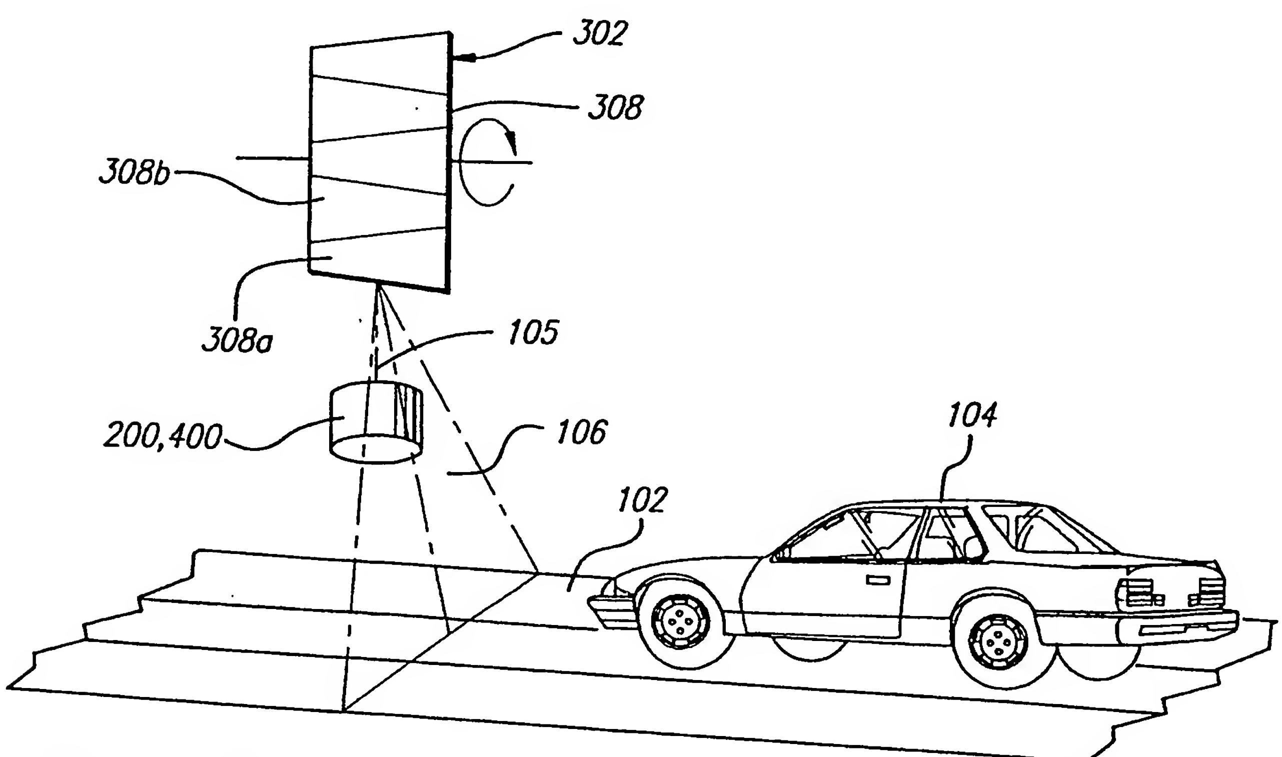
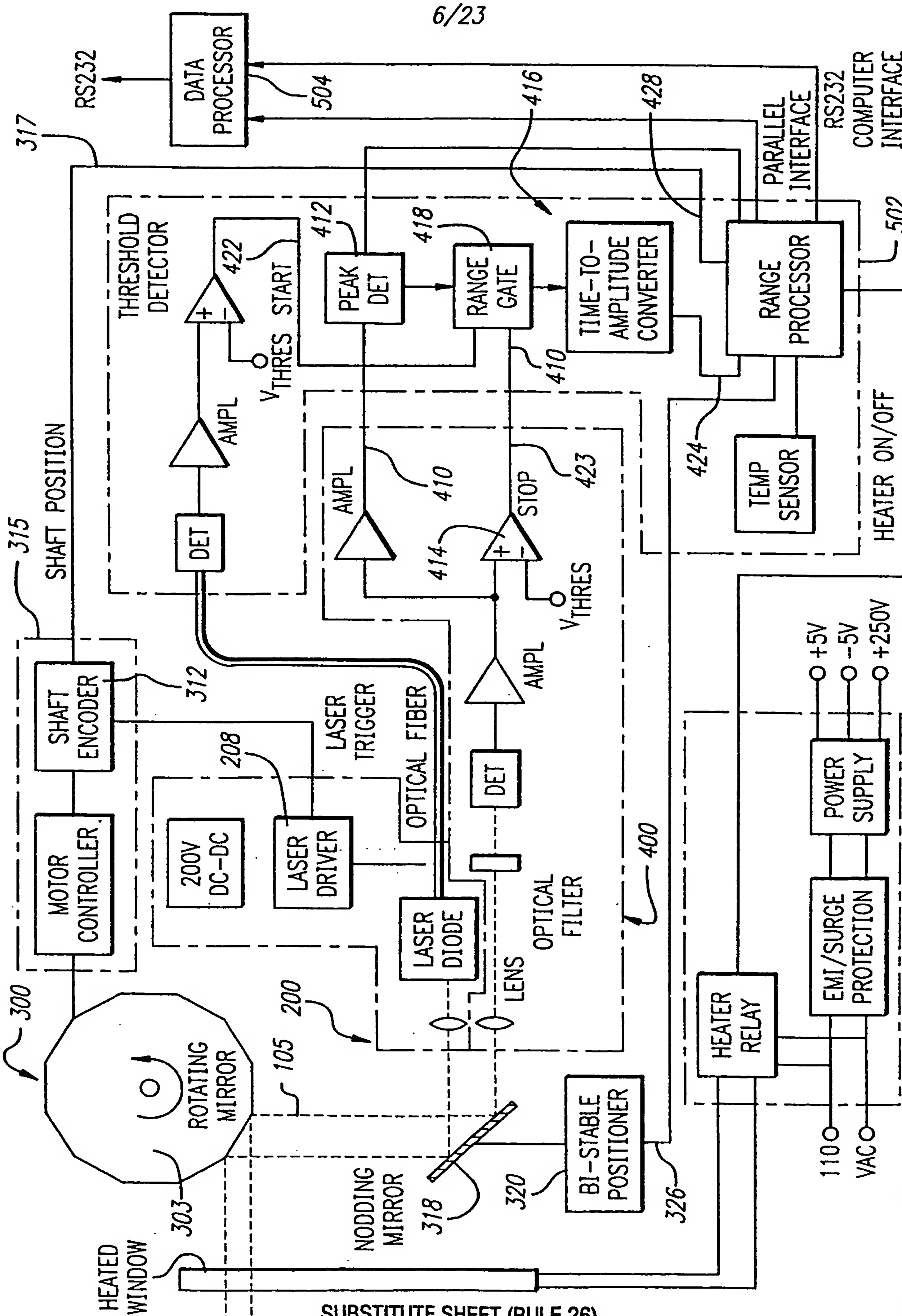

302
308
308b
308a
105
200,400
106
104
102

FIG. 7



SUBSTITUTE SHEET (RULE 26)

FIG. 8

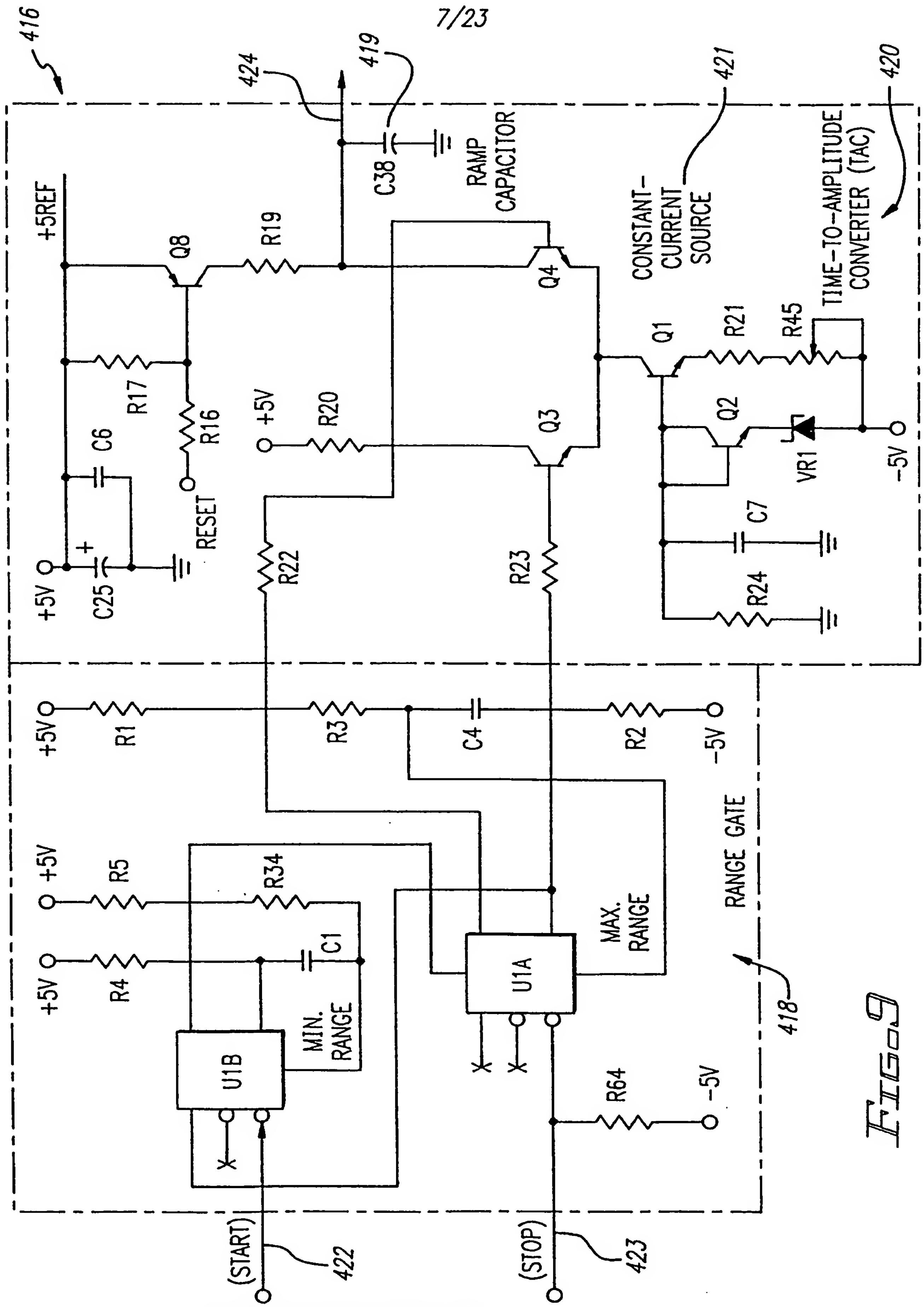

416
424
419
420
421
+5REF
Q8
R19
C38
RAMP CAPACITOR
CONSTANT-CURRENT SOURCE
TIME-TO-AMPLITUDE CONVERTER (TAC)
Q4
Q1
R21
R45
R17
R16
+5V
R20
Q3
Q2
VR1
-5V
C6
RESET
C7
+5V
C25
R22
R23
R24
+5V
R1
R3
C4
R2
-5V
+5V
R5
R34
+5V
R4
C1
U1A
MAX. RANGE
RANGE GATE
418
U1B
MIN. RANGE
R64
-5V
(START)
422
(STOP)
423

FIG-9

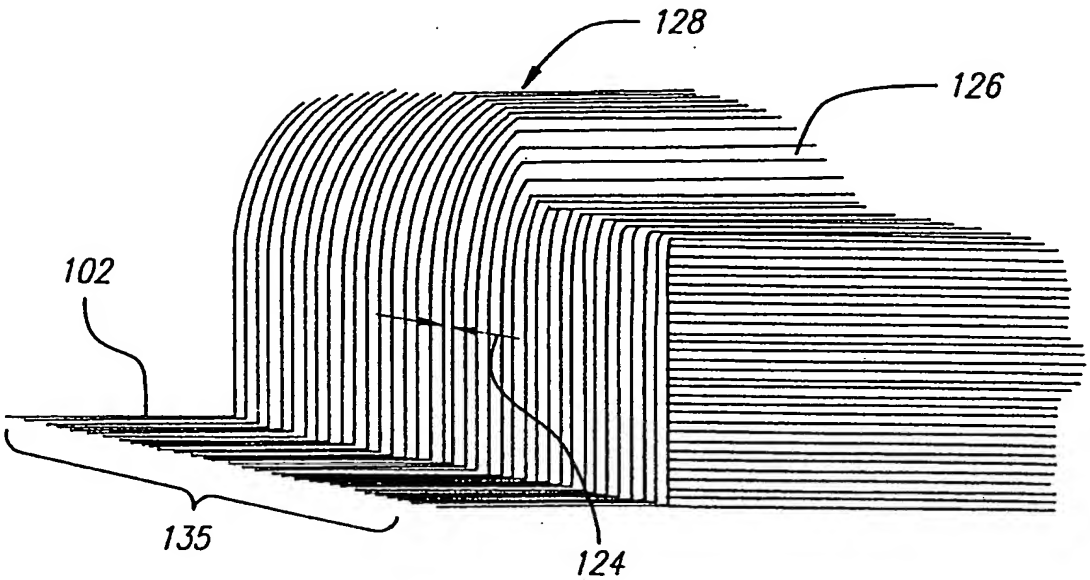


FIG. 10

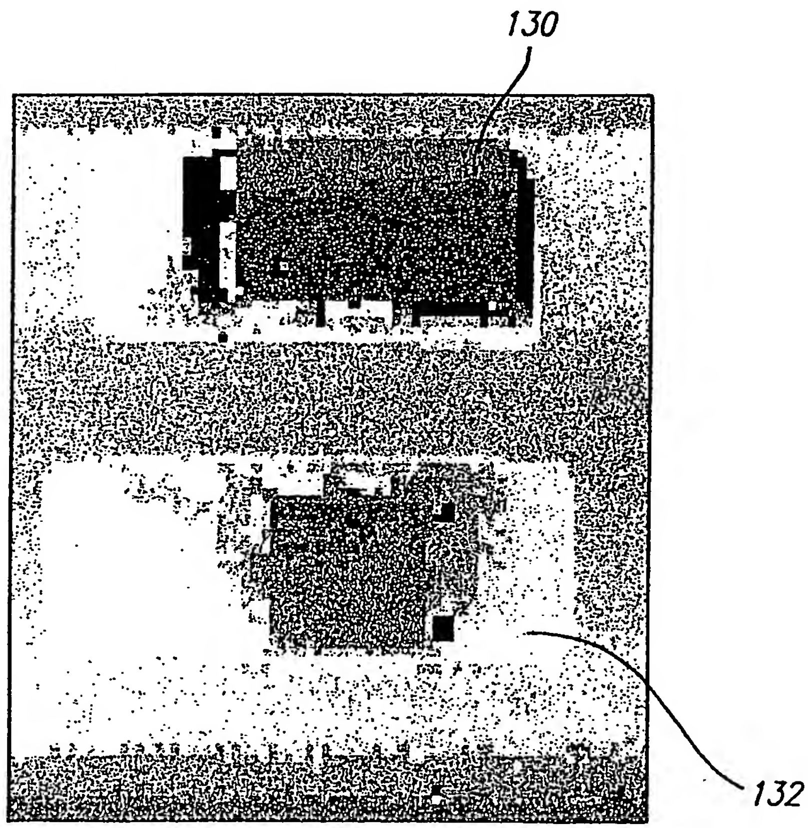


FIG. 11

SUBSTITUTE SHEET (RULE 26)

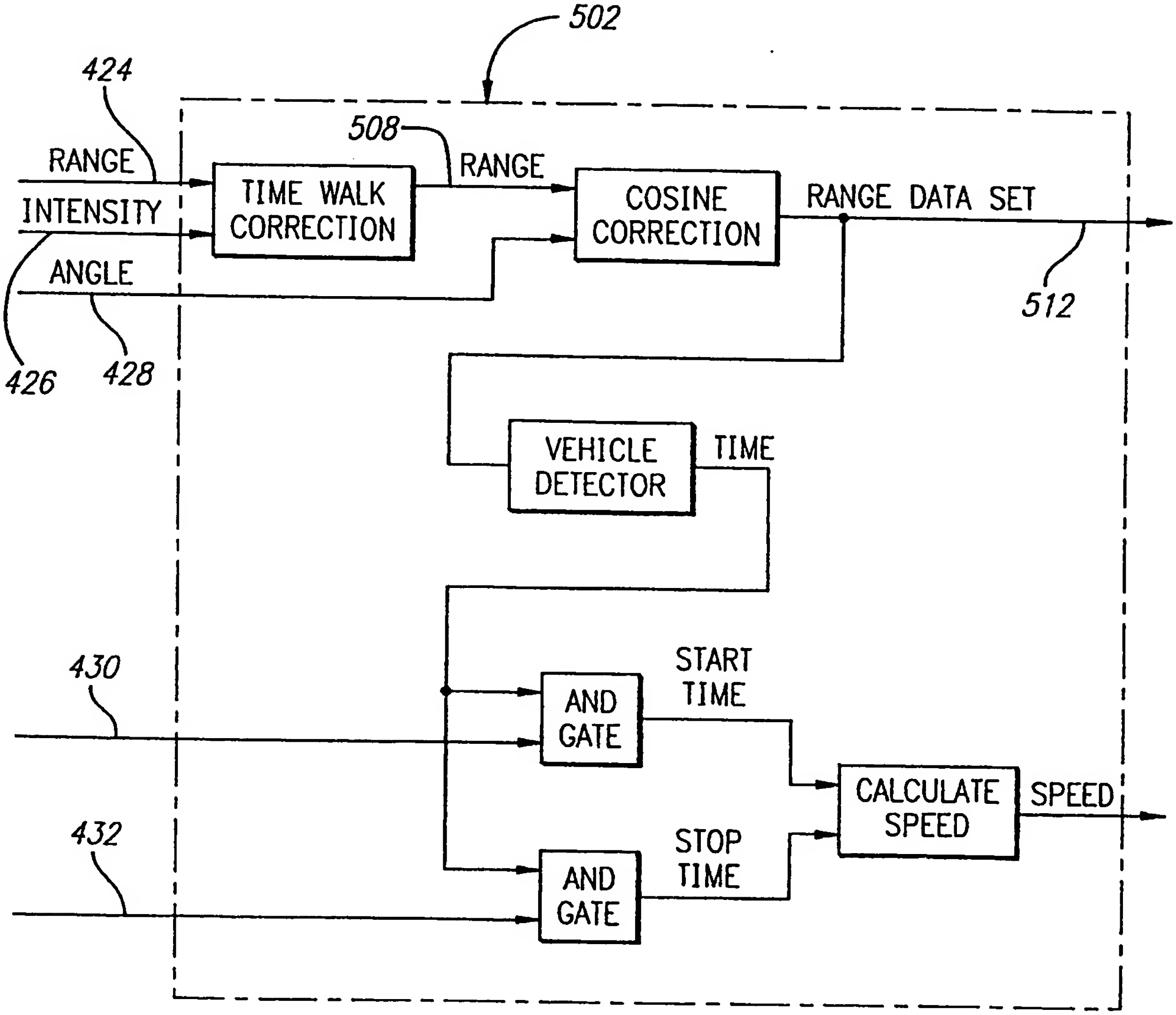


FIG. 12A

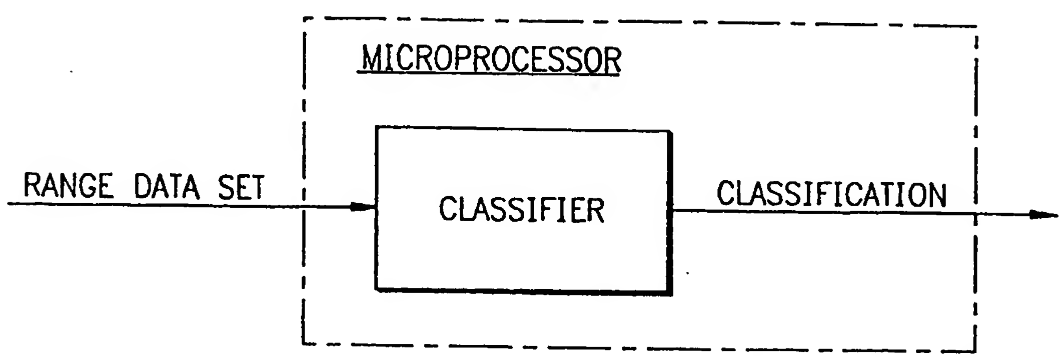


FIG. 12B

SUBSTITUTE SHEET (RULE 26)

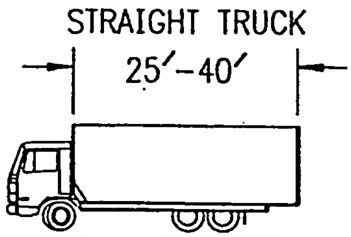


FIG. 13A

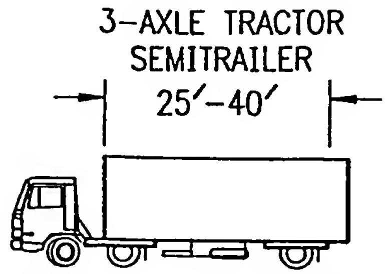


FIG. 13B

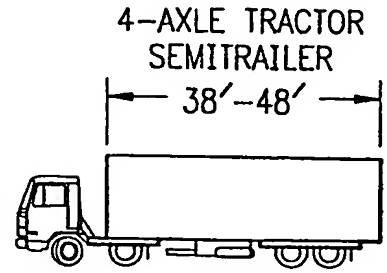


FIG. 13C

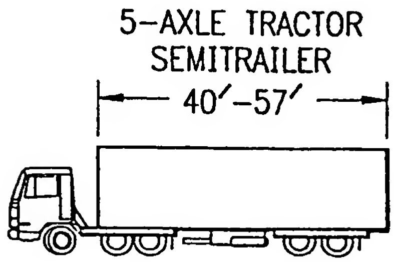


FIG. 13D

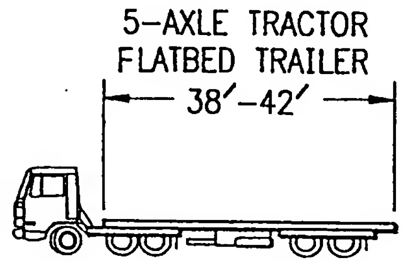


FIG. 13E

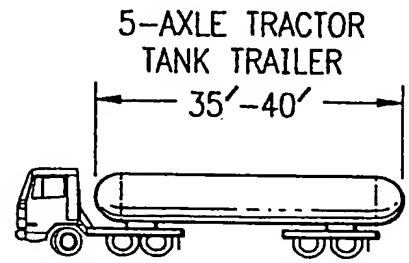


FIG. 13F

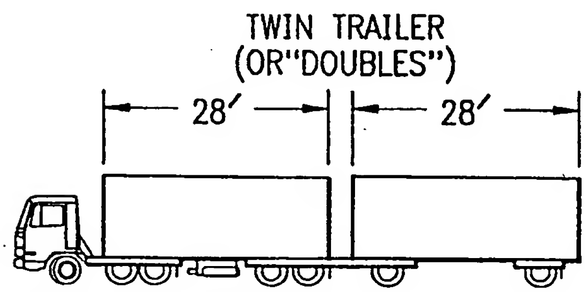


FIG. 13G

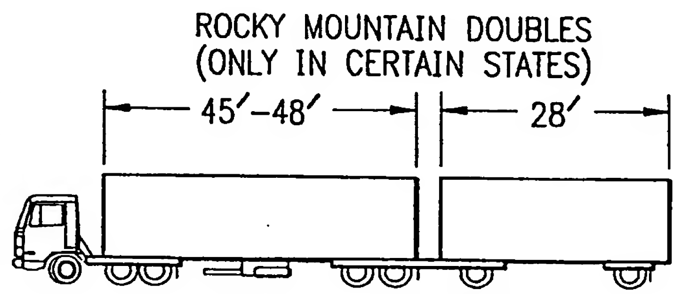


FIG. 13H

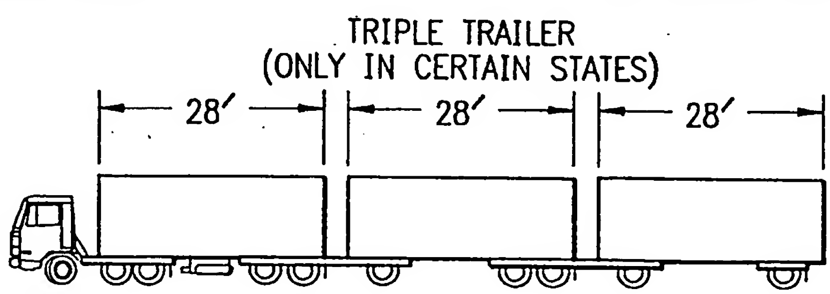


FIG. 13I

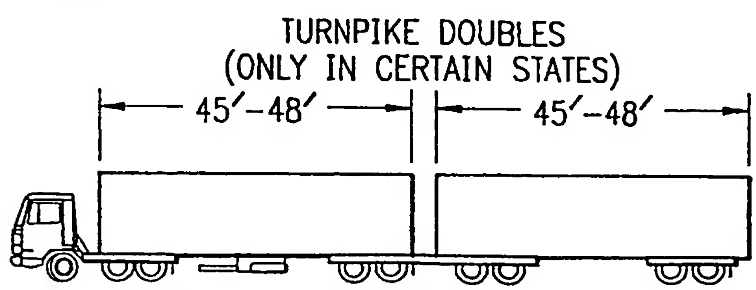


FIG. 13J

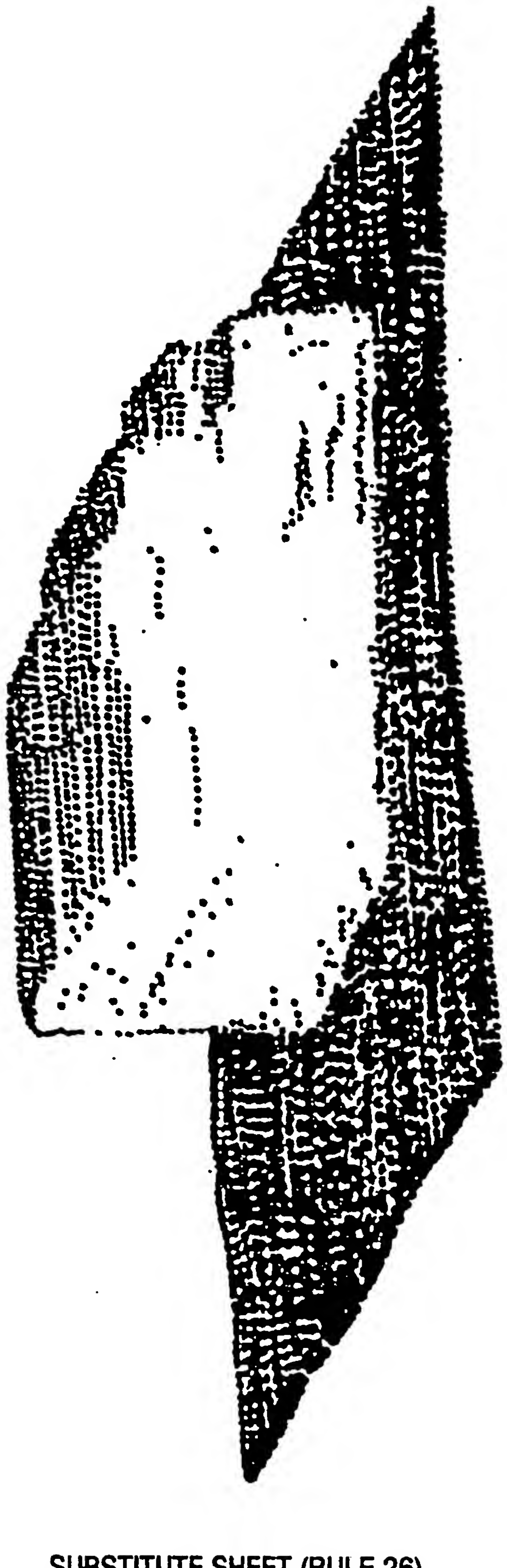


FIG. 13K

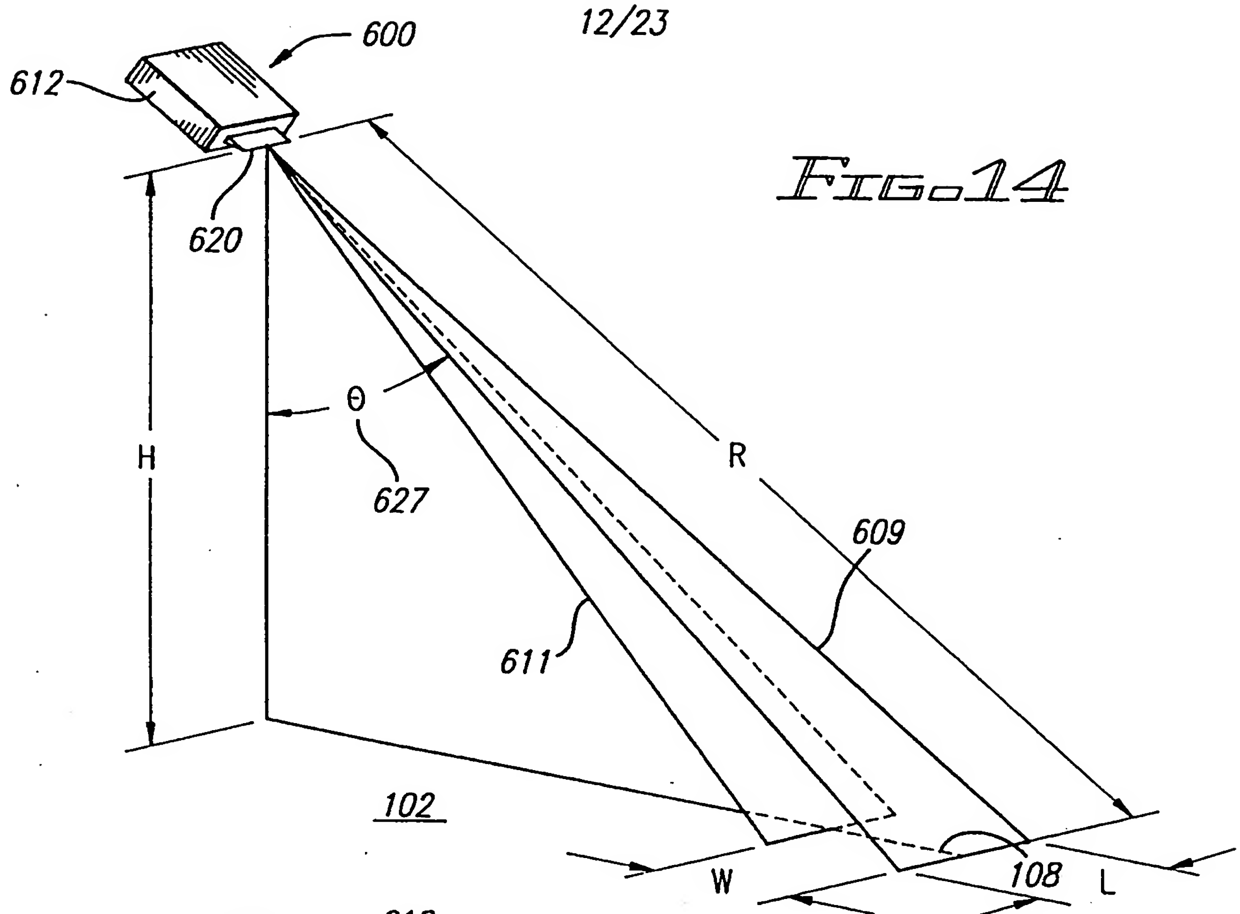

600
612
620
Θ
627
H
R
609
611
102
W
108
L

FIG. 14

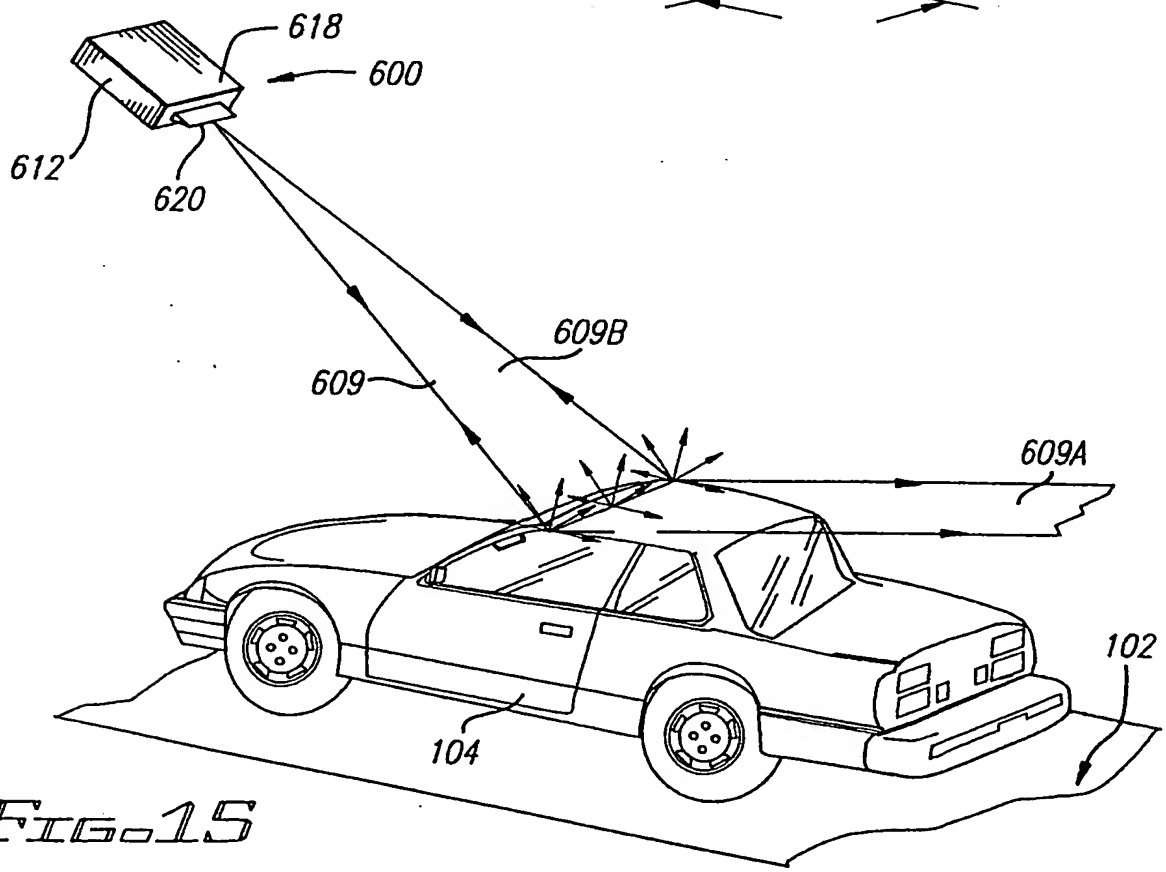

618
600
612
620
609B
609
609A
102
104

FIG. 15

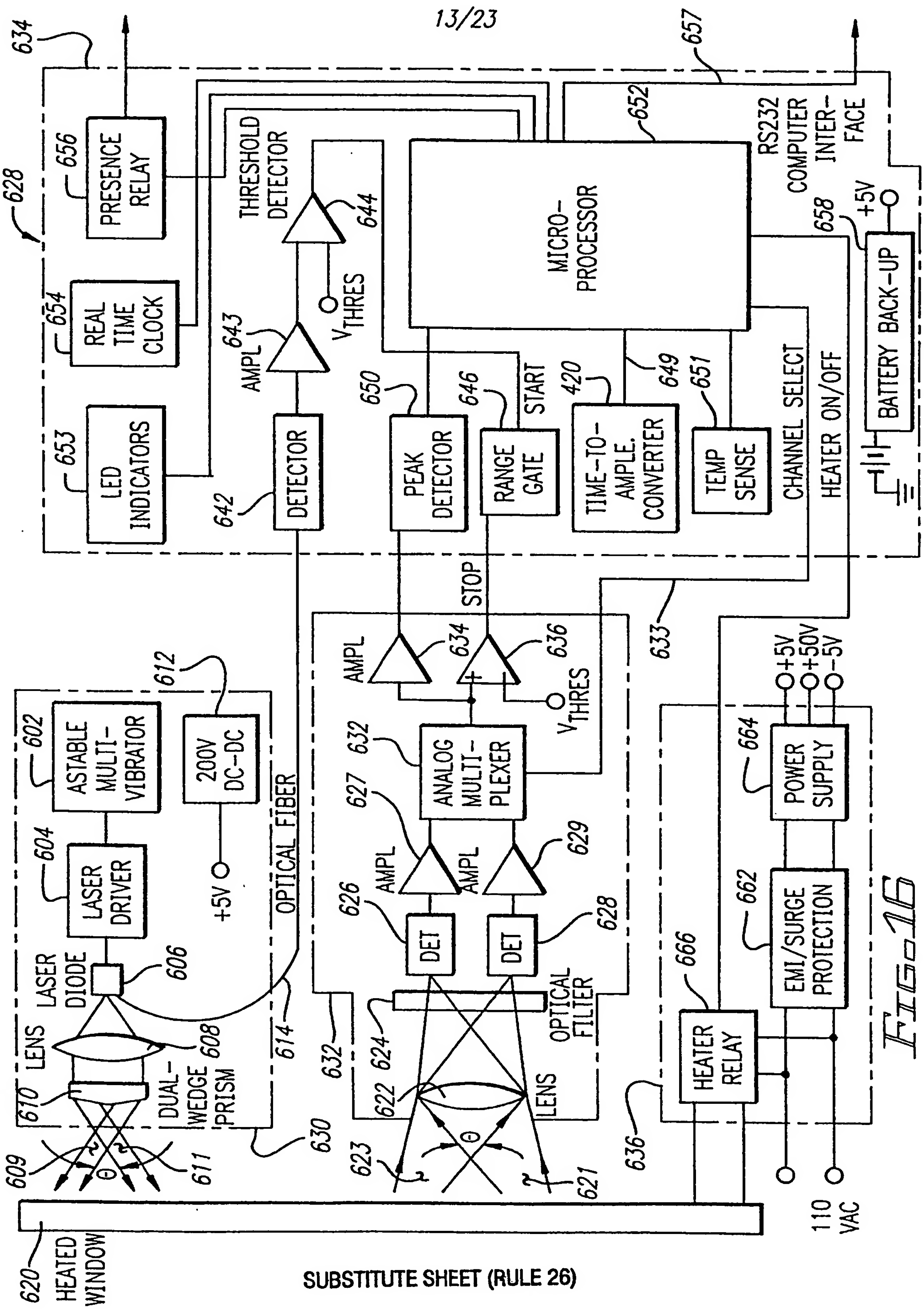

634
628
656
PRESENCE RELAY
654
REAL TIME CLOCK
653
LED INDICATORS
THRESHOLD DETECTOR
644
643
AMPL
V_{THRES}
642
DETECTOR
652
MICRO-PROCESSOR
650
PEAK DETECTOR
646
RANGE GATE
START
420
TIME-TO-AMPLE. CONVERTER
649
651
TEMP SENSE
CHANNEL SELECT
HEATER ON/OFF
657
RS232 COMPUTER INTER-FACE
658
+5V
BATTERY BACK-UP
STOP
633
AMPL
634
636
V_{THRES}
632
ANALOG MULTI-PLEXER
627
629
AMPL
AMPL
626
DET
DET
628
OPTICAL FILTER
624
632
622
LENS
623
621
602
ASTABLE MULTI-VIBRATOR
612
200V DC-DC
604
LASER DRIVER
+5V
OPTICAL FIBER
LASER DIODE
606
LENS
608
614
610
DUAL-WEDGE PRISM
630
609
611
620
HEATED WINDOW
664
POWER SUPPLY
+5V
+50V
-5V
662
EMI/SURGE PROTECTION
666
HEATER RELAY
636
110 VAC

FIG. 16

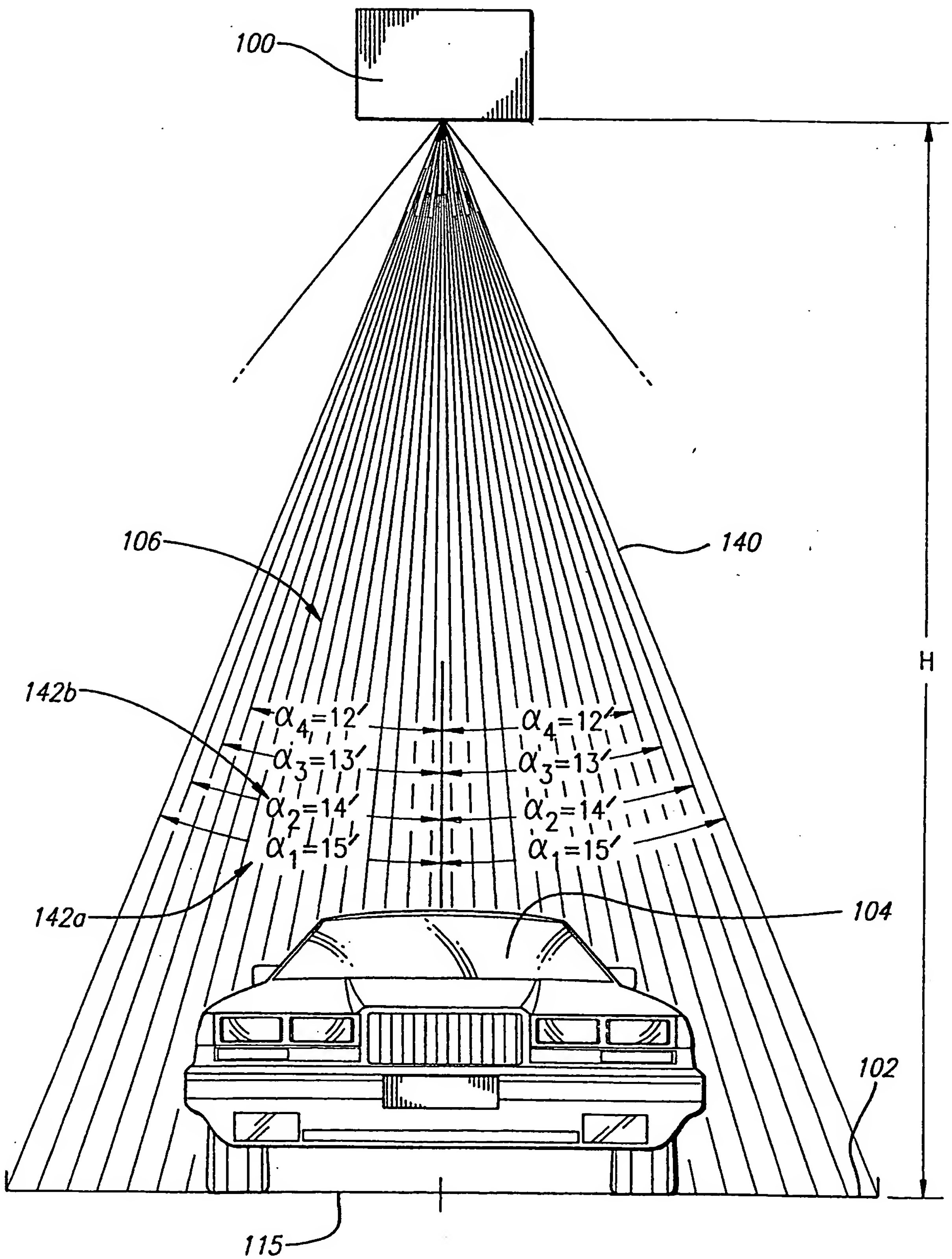

100
106
140
H
142b
α_4=12′
α_3=13′
α_2=14′
α_1=15′
α_4=12′
α_3=13′
α_2=14′
α_1=15′
142a
104
102
115

FIG. 17

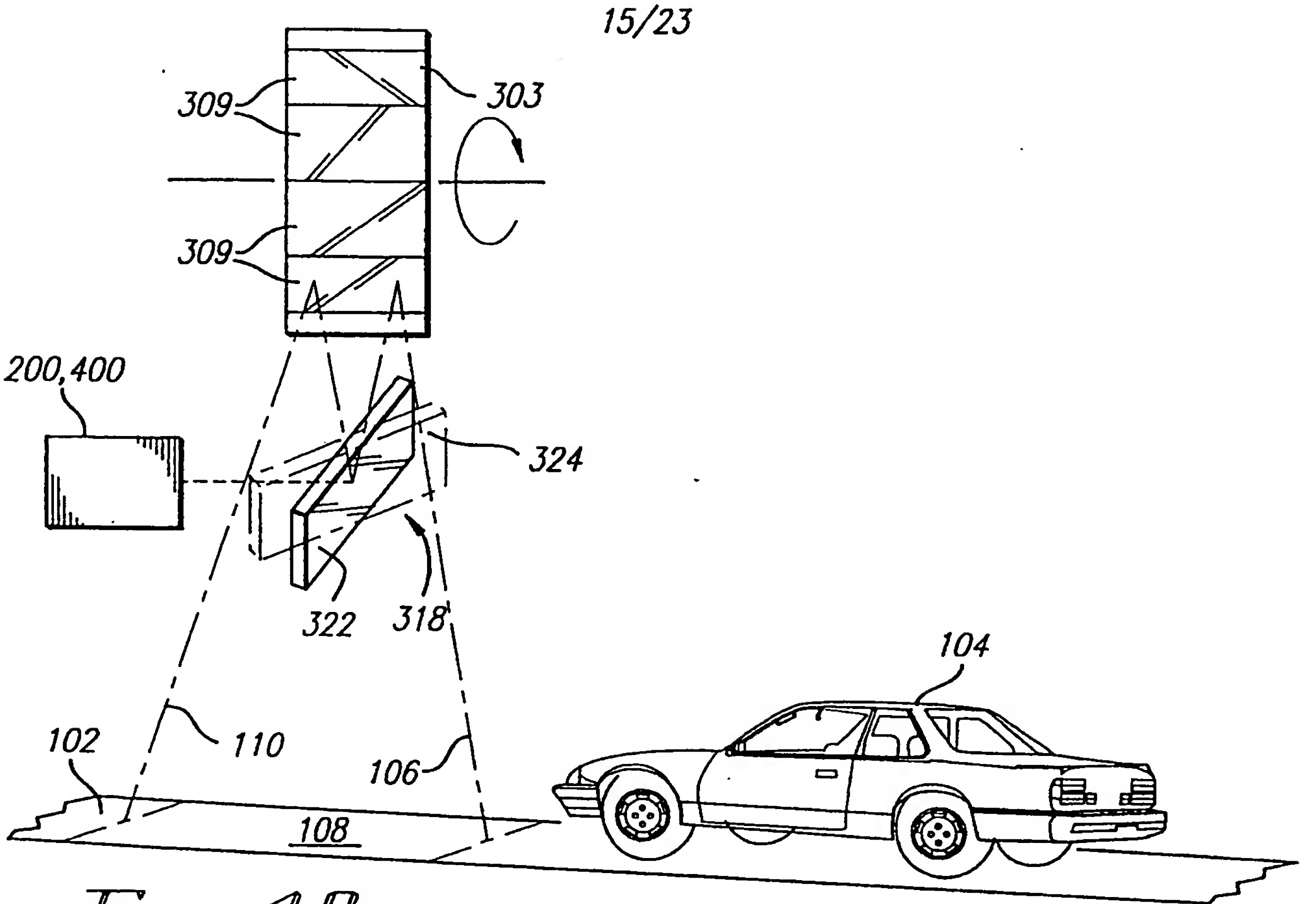

309
303
309
200,400
324
322
318
104
102
110
106
108

FIG. 18

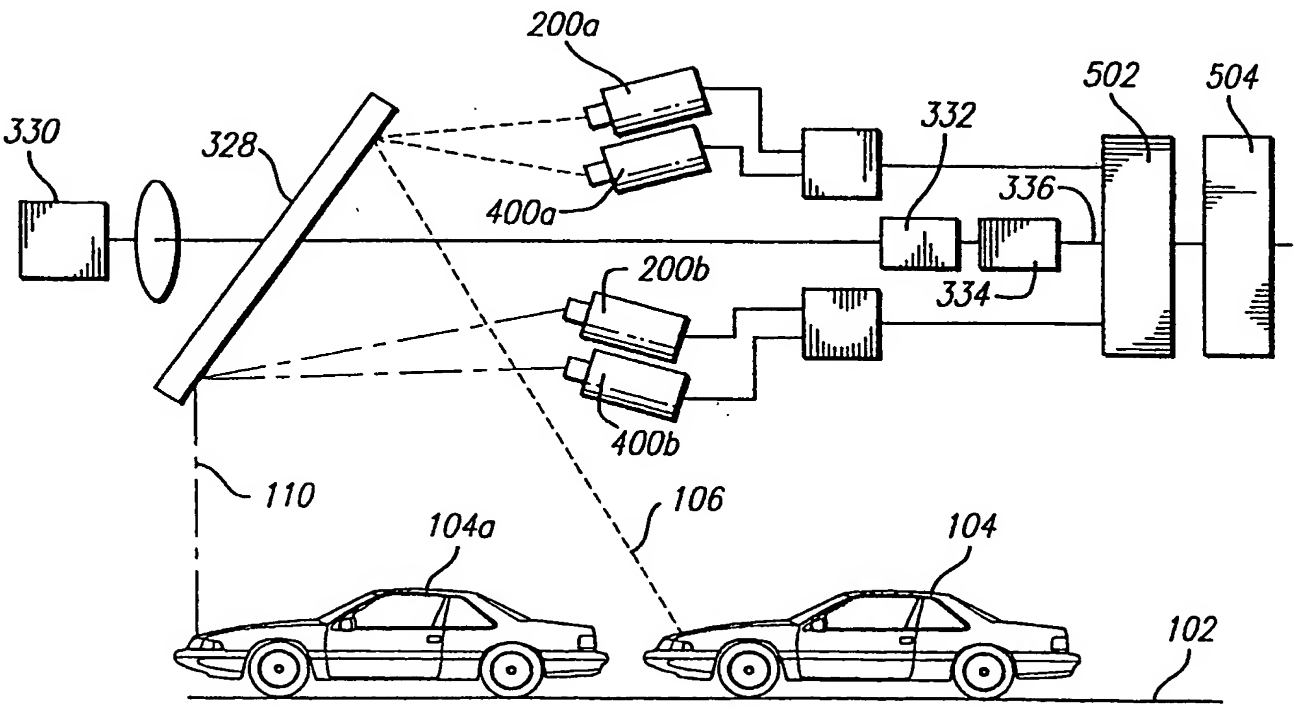

200a
330
328
332
502
504
336
400a
200b
334
400b
110
106
104a
104
102

FIG. 19

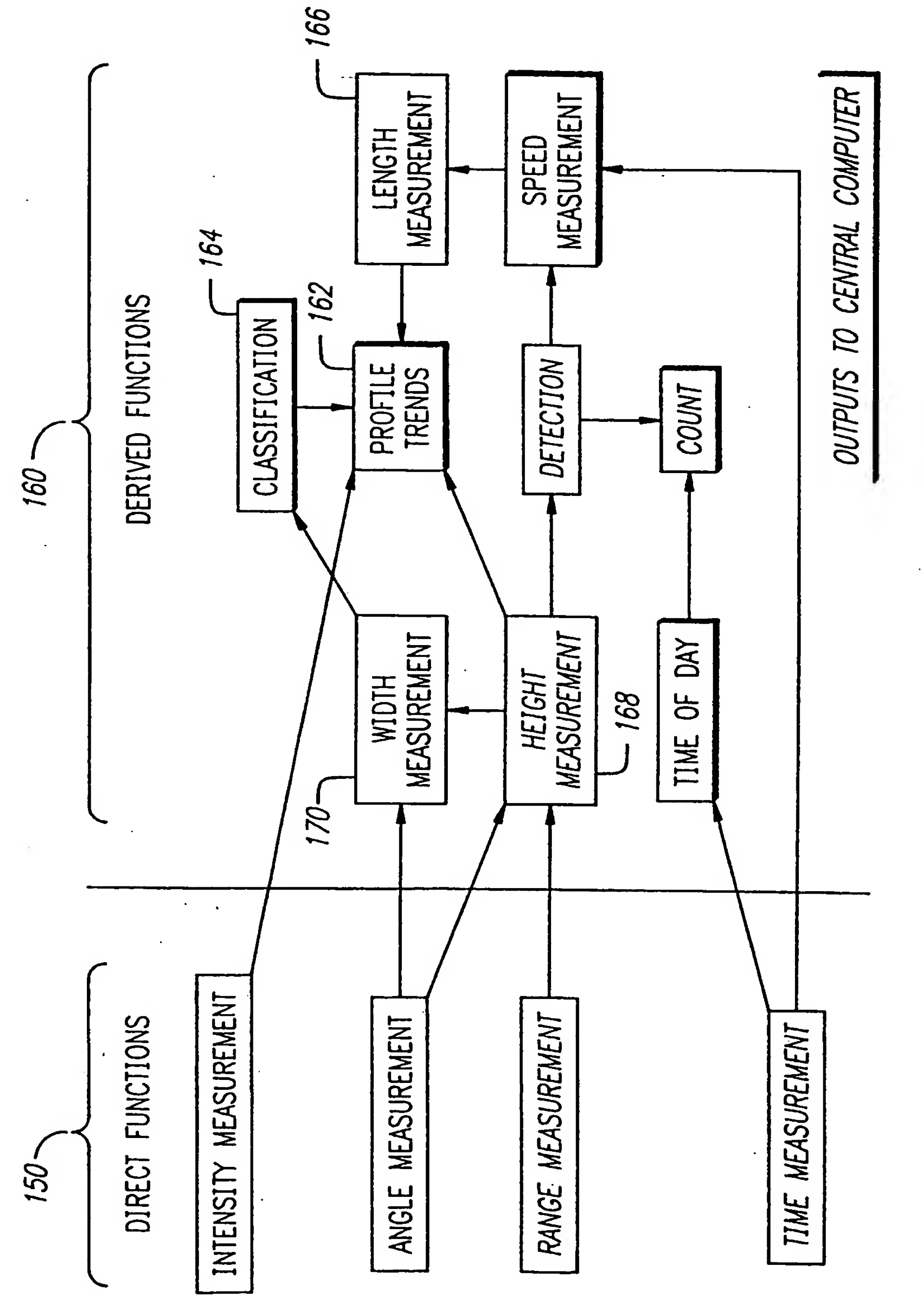

DIRECT FUNCTIONS
150
INTENSITY MEASUREMENT
ANGLE MEASUREMENT
RANGE MEASUREMENT
TIME MEASUREMENT
DERIVED FUNCTIONS
160
WIDTH MEASUREMENT
170
HEIGHT MEASUREMENT
168
TIME OF DAY
CLASSIFICATION
164
PROFILE TRENDS
162
DETECTION
COUNT
LENGTH MEASUREMENT
166
SPEED MEASUREMENT
OUTPUTS TO CENTRAL COMPUTER

FIG. 20

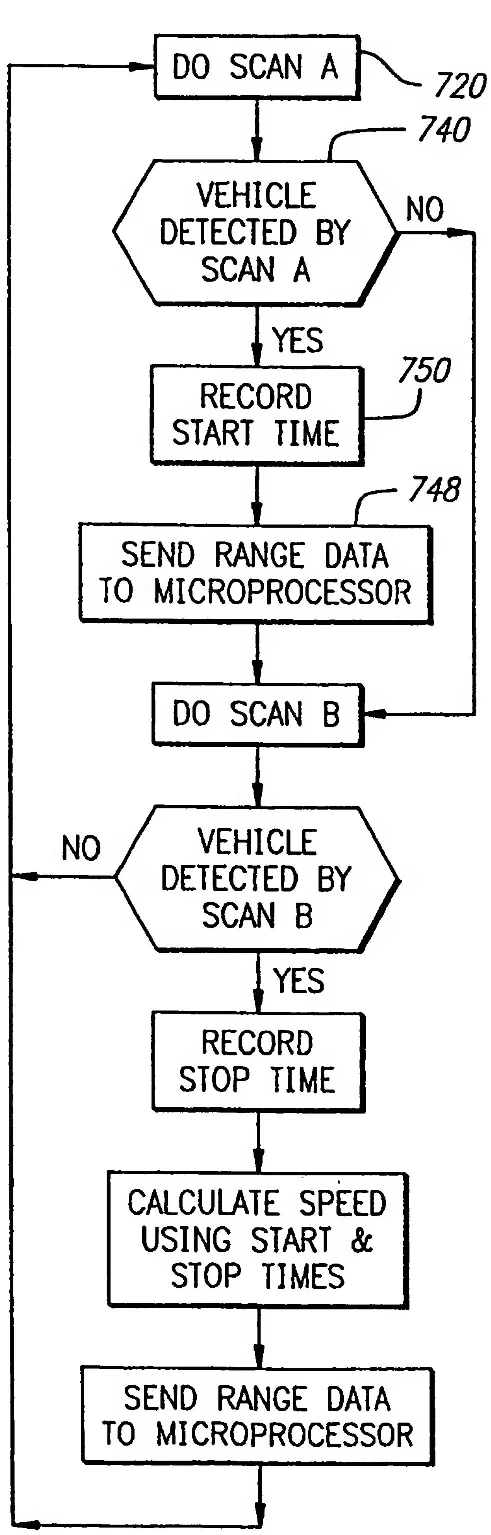

DO SCAN A
720
740
VEHICLE DETECTED BY SCAN A
NO
YES
RECORD START TIME
750
748
SEND RANGE DATA TO MICROPROCESSOR
DO SCAN B
VEHICLE DETECTED BY SCAN B
NO
YES
RECORD STOP TIME
CALCULATE SPEED USING START & STOP TIMES
SEND RANGE DATA TO MICROPROCESSOR

FIG. 21

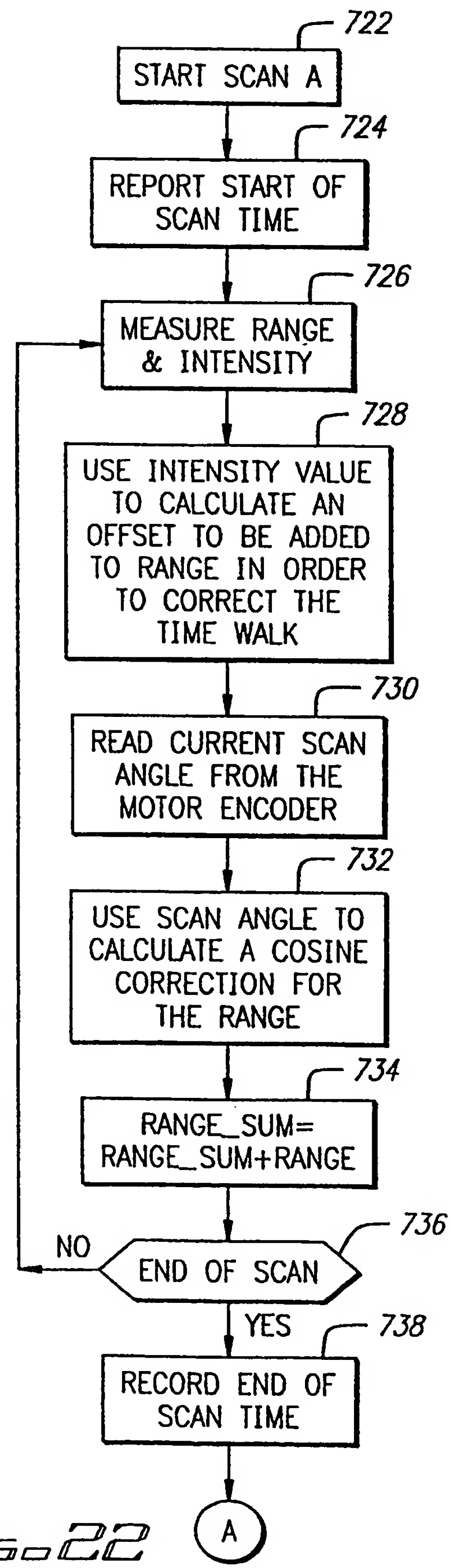

722
START SCAN A
724
REPORT START OF SCAN TIME
726
MEASURE RANGE & INTENSITY
728
USE INTENSITY VALUE TO CALCULATE AN OFFSET TO BE ADDED TO RANGE IN ORDER TO CORRECT THE TIME WALK
730
READ CURRENT SCAN ANGLE FROM THE MOTOR ENCODER
732
USE SCAN ANGLE TO CALCULATE A COSINE CORRECTION FOR THE RANGE
734
RANGE_SUM= RANGE_SUM+RANGE
736
NO
END OF SCAN
YES
738
RECORD END OF SCAN TIME
A

FIG. 22

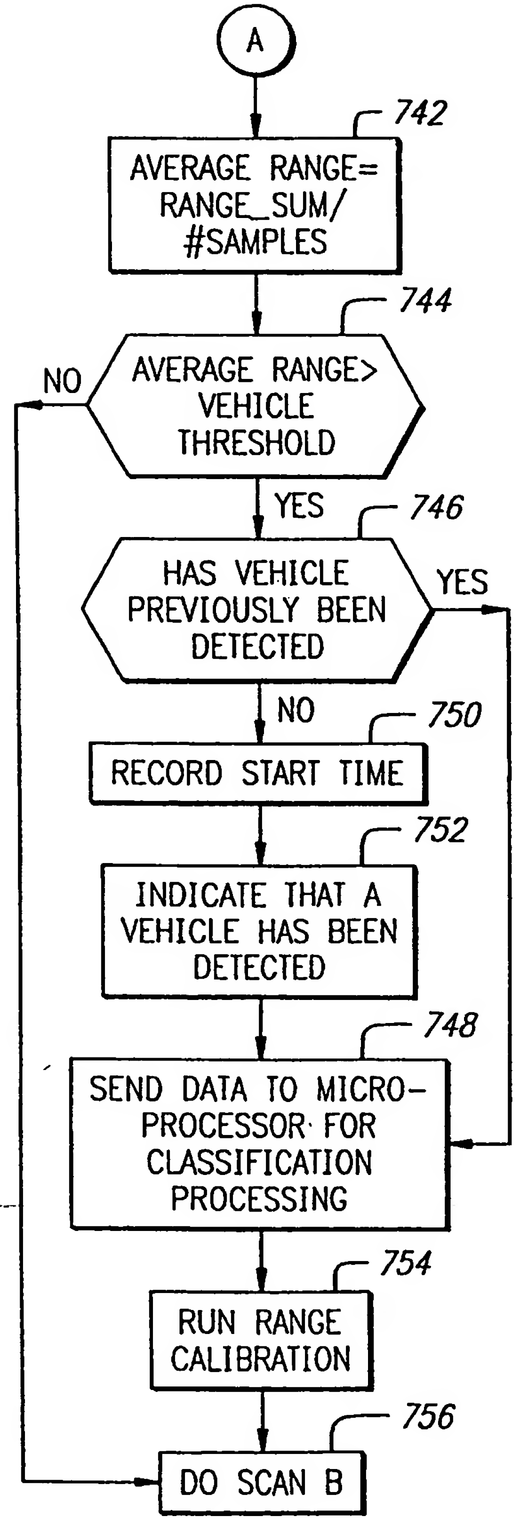

A
742
AVERAGE RANGE= RANGE_SUM/ #SAMPLES
744
AVERAGE RANGE> VEHICLE THRESHOLD
NO
YES
746
HAS VEHICLE PREVIOUSLY BEEN DETECTED
YES
NO
750
RECORD START TIME
752
INDICATE THAT A VEHICLE HAS BEEN DETECTED
748
SEND DATA TO MICRO-PROCESSOR FOR CLASSIFICATION PROCESSING
754
RUN RANGE CALIBRATION
756
DO SCAN B

FIG. 23

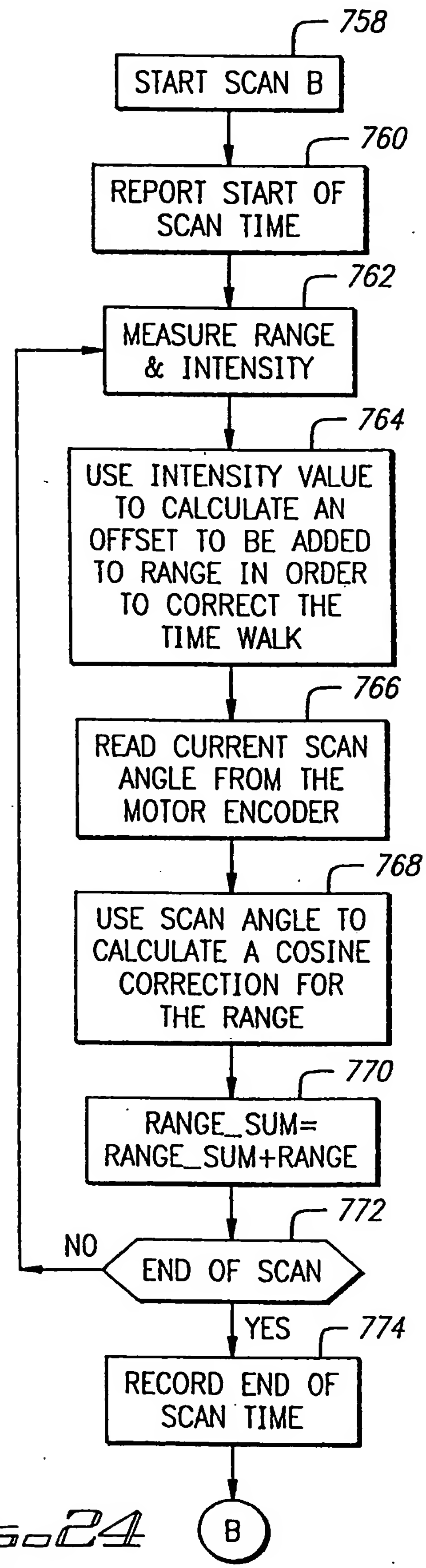

758
START SCAN B
760
REPORT START OF SCAN TIME
762
MEASURE RANGE & INTENSITY
764
USE INTENSITY VALUE TO CALCULATE AN OFFSET TO BE ADDED TO RANGE IN ORDER TO CORRECT THE TIME WALK
766
READ CURRENT SCAN ANGLE FROM THE MOTOR ENCODER
768
USE SCAN ANGLE TO CALCULATE A COSINE CORRECTION FOR THE RANGE
770
RANGE_SUM= RANGE_SUM+RANGE
772
END OF SCAN
NO
YES
774
RECORD END OF SCAN TIME
B

FIG. 24

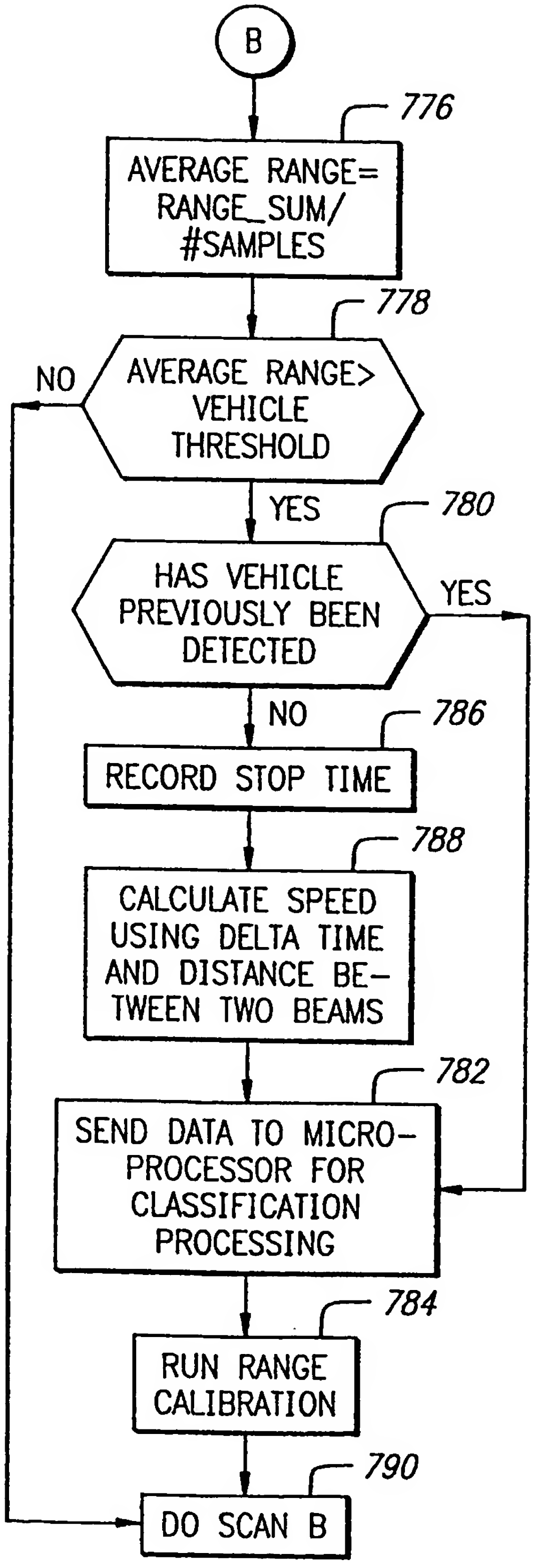

B
776
AVERAGE RANGE= RANGE_SUM/ #SAMPLES
778
AVERAGE RANGE> VEHICLE THRESHOLD
NO
YES
780
HAS VEHICLE PREVIOUSLY BEEN DETECTED
YES
NO
786
RECORD STOP TIME
788
CALCULATE SPEED USING DELTA TIME AND DISTANCE BE-TWEEN TWO BEAMS
782
SEND DATA TO MICRO-PROCESSOR FOR CLASSIFICATION PROCESSING
784
RUN RANGE CALIBRATION
790
DO SCAN B

FIG. 25

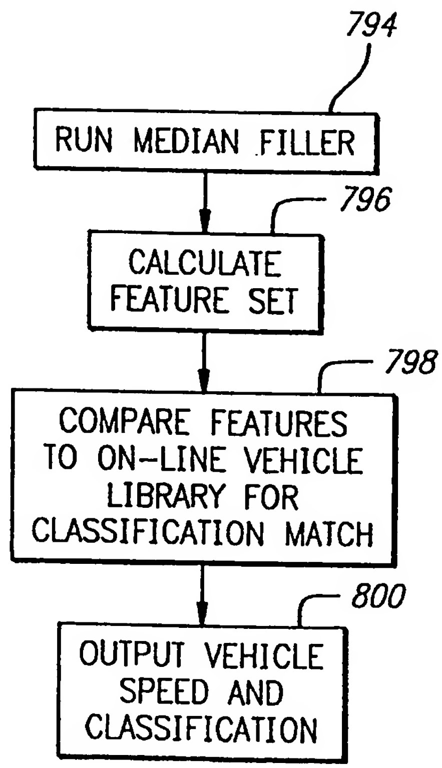

794
RUN MEDIAN FILLER
796
CALCULATE FEATURE SET
798
COMPARE FEATURES TO ON-LINE VEHICLE LIBRARY FOR CLASSIFICATION MATCH
800
OUTPUT VEHICLE SPEED AND CLASSIFICATION

FIG. 26

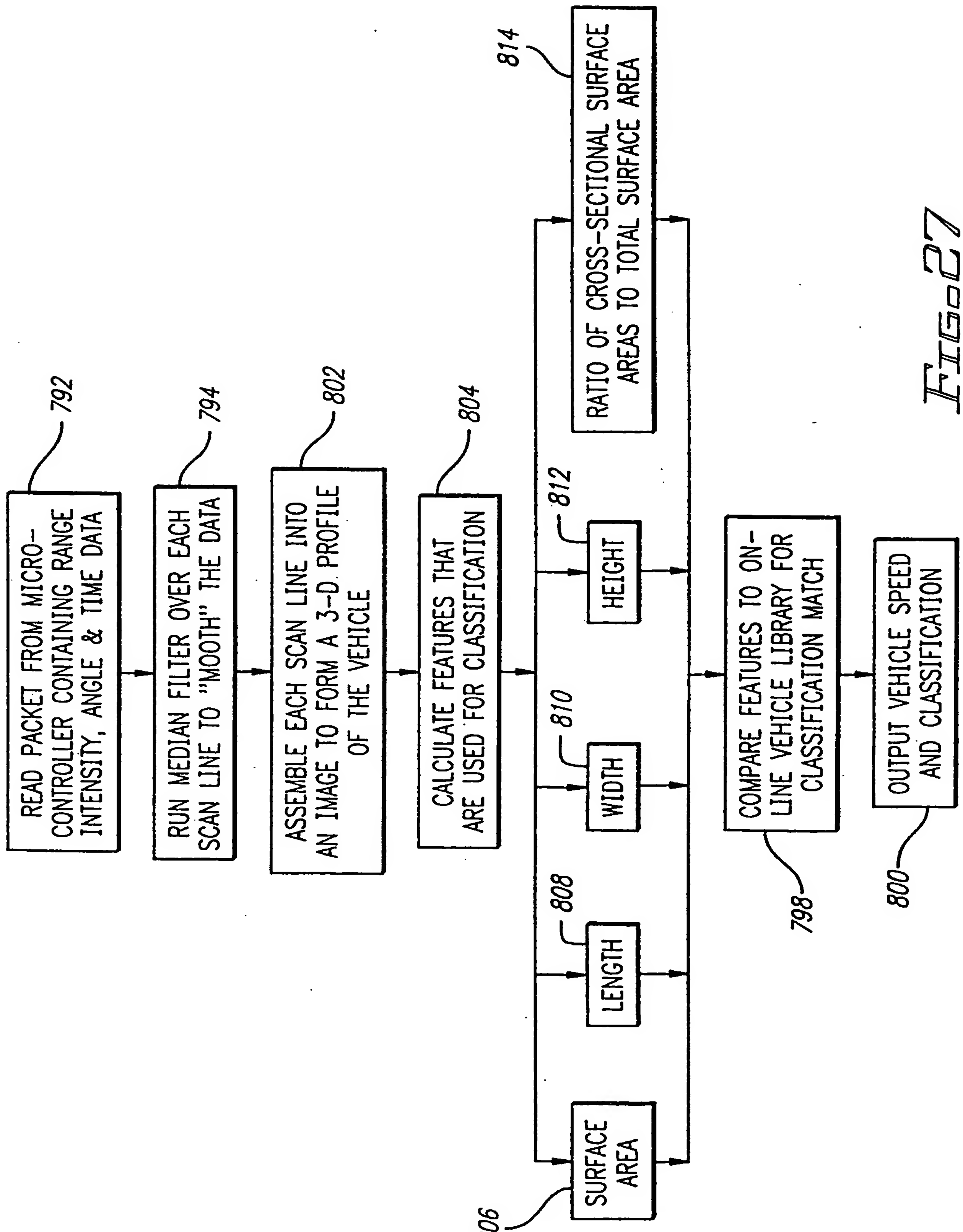

READ PACKET FROM MICRO-CONTROLLER CONTAINING RANGE INTENSITY, ANGLE & TIME DATA
792
RUN MEDIAN FILTER OVER EACH SCAN LINE TO "MOOTH" THE DATA
794
ASSEMBLE EACH SCAN LINE INTO AN IMAGE TO FORM A 3-D PROFILE OF THE VEHICLE
802
CALCULATE FEATURES THAT ARE USED FOR CLASSIFICATION
804
SURFACE AREA
806
LENGTH
808
WIDTH
810
HEIGHT
812
RATIO OF CROSS-SECTIONAL SURFACE AREAS TO TOTAL SURFACE AREA
814
COMPARE FEATURES TO ON-LINE VEHICLE LIBRARY FOR CLASSIFICATION MATCH
798
OUTPUT VEHICLE SPEED AND CLASSIFICATION
800

FIG. 27

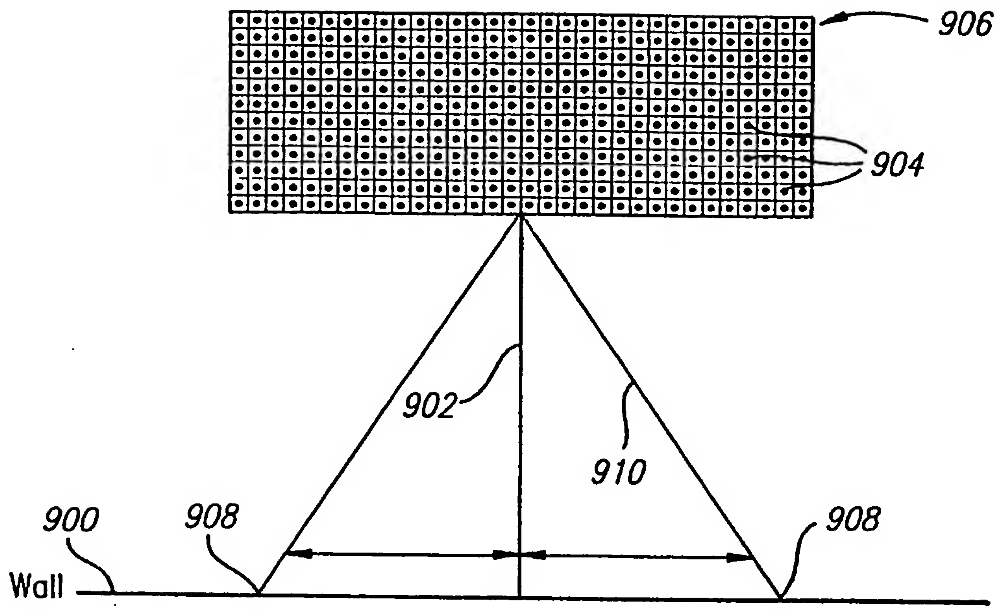


FIG. 28

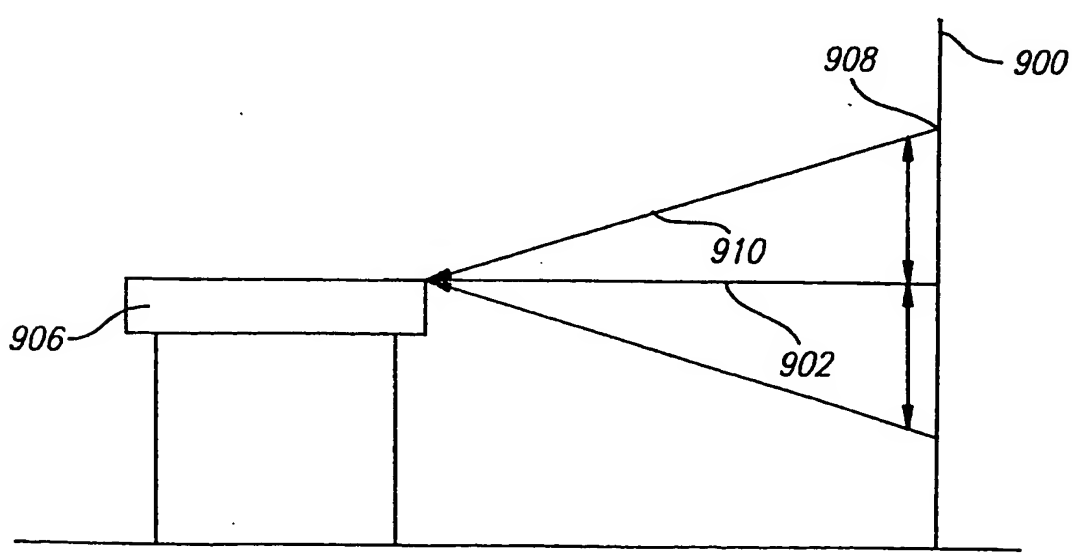


FIG. 29

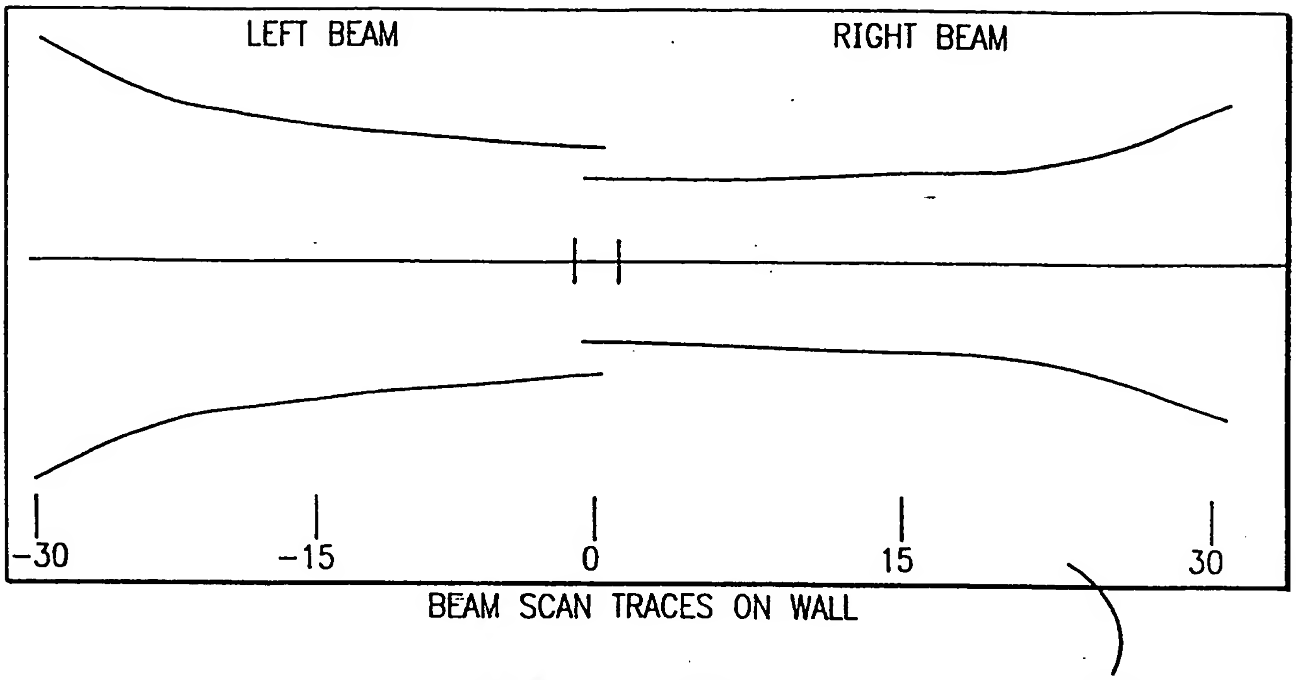


FIG. 30

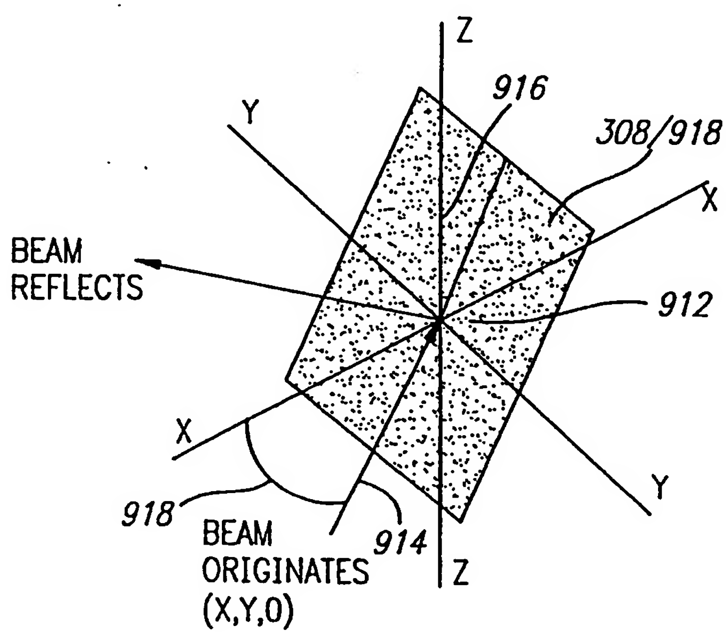


FIG. 31

SUBSTITUTE SHEET (RULE 26)

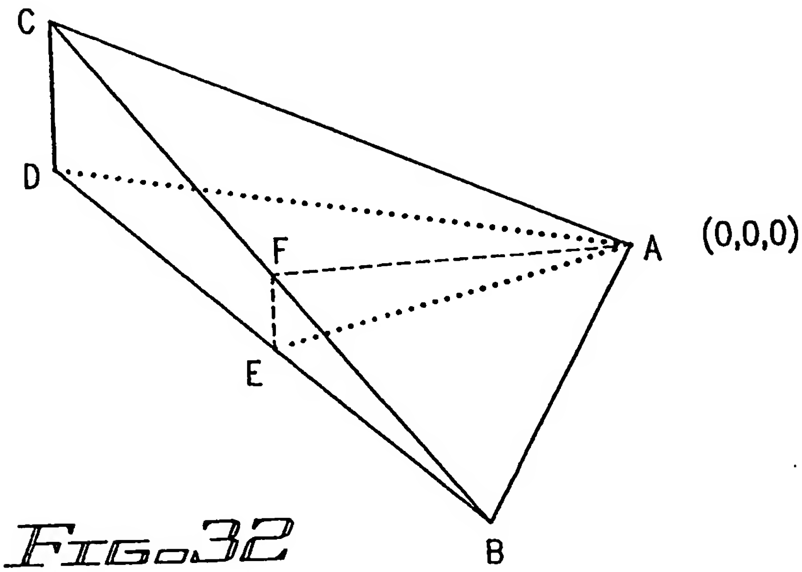


FIG. 32

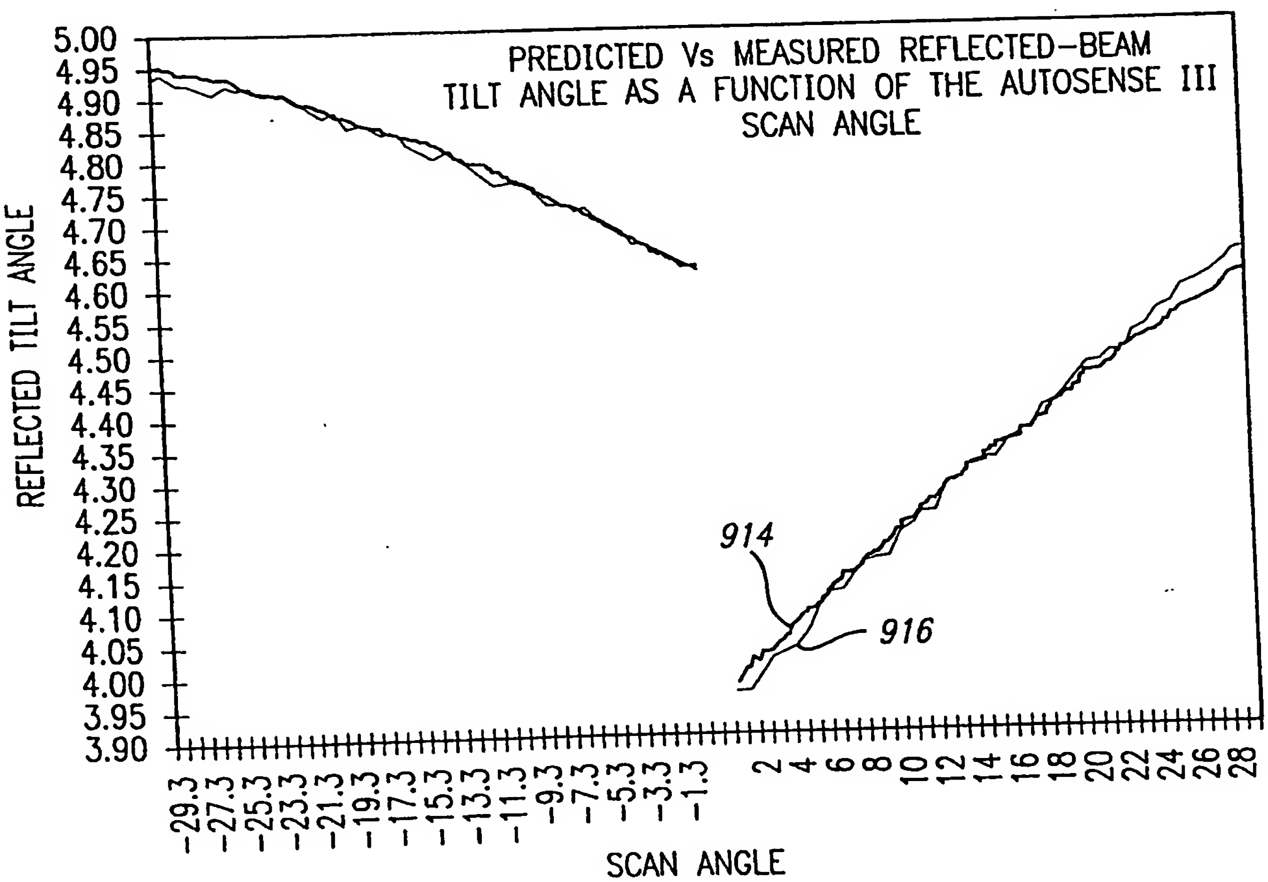


FIG. 33

SUBSTITUTE SHEET (RULE 26)

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US97/18628

A. CLASSIFICATION OF SUBJECT MATTER
IPC(6) :G01C 03/08; G01B 11/24
US CL :356/4.01, 5.01, 376, 398
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 356/4.01, 5.01, 376, 398

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

None

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

None

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 4,335,962 A (DIMATTEO) et al. 22 June 1982, whole document.	1-12
A	US 5,111,056 A (YOSHIMURA et al.) 05 May 1992, whole document.	1-12
A	US 5,528,354 A (UWIRA) 18 June 1996, whole document.	1-12

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

*	Special categories of cited documents:	"T"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A"	document defining the general state of the art which is not considered to be of particular relevance	"X"	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"E"	earlier document published on or after the international filing date	"Y"	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"L"	document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"&"	document member of the same patent family
"O"	document referring to an oral disclosure, use, exhibition or other means		
"P"	document published prior to the international filing date but later than the priority date claimed		

Date of the actual completion of the international search
06 DECEMBER 1997

Date of mailing of the international search report
16 MAR 1998

Name and mailing address of the ISA/US
Commissioner of Patents and Trademarks
Box PCT
Washington, D.C. 20231
Facsimile No. (703) 305-3230

Authorized officer Diane Gonlieyn
for MARK HELLNER
Telephone No. (703) 306-4155